INTRODUCTION TO RADIOFREQUENCY SYSTEMS FOR PARTICLE ACCELERATORS

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OVERVIEW

- ✓ Introduction
- ✓ Building blocks
- ✓ Accelerating structures
- ✓ Power sources
- ✓ Power transmission
- ✓ LLRF
- ✓ Summary
- ✓ References and Bibliography

INTRODUCTION

Historical Background

and

Tasks of the RF Systems

HISTORICAL BACKGROUND DC ACCELERATORS

Tens of kV for x-ray tubes are easily produced by transformer rectifier power supplies

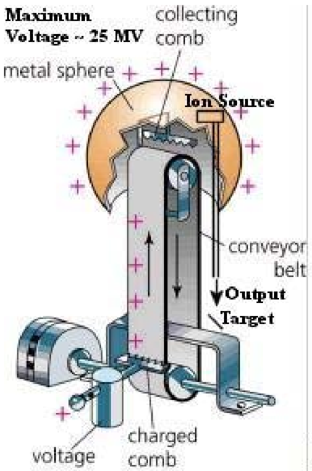
Cockroft-Walton (1932 used for first accelerator experiments with protons)

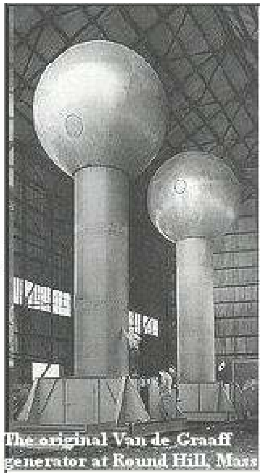
- ✓ Based on the principle of charging capacitors and discharging them in series
- ✓ Used later as pre-accelerator for proton machines (typically up to 750 KV)
- ✓ Now replaced by radio-frequency quadrupoles.

National Science Museum, London UK

Van de Graaff generator

- ✓ It is an electrostatic machine which uses a moving belt to accumulate very high voltages on a hollow metal globe.
- ✓ Ion source is located inside the high voltage terminal and ions are accelerated by the electric voltage between the high-voltage supply and ground. Typical range around 15 MeV.
- ✓ Energy gain can be doubled with the tandem principle





Energy gain in DC accelerators limited by the max potential difference that can be held

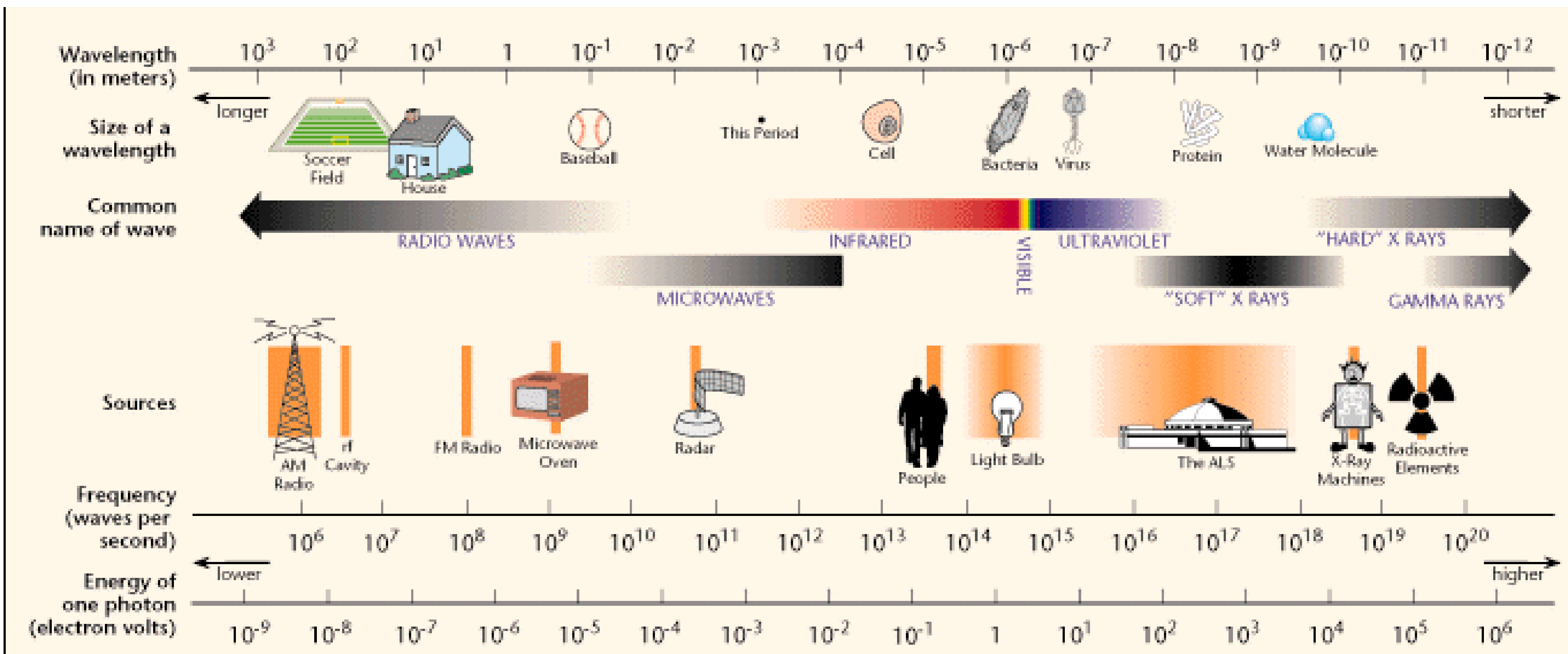
HISTORICAL BACKGROUND DC ACCELERATORS

- ✓ Limitation of DC accelerators can be overcome using time varying electromagnetic field.
- ✓ Resonant acceleration by means of time-varying fields across the drift tubes proposed by Ising (1924)
- ✓ This lead to the development of the first proof of principle linear accelerator by Wideroe (1927).
- ✓ First cyclotron was built in 1931
- ✓ From these developments RF becomes the centre of particle accelerators.
- ✓ Following technological developments allowed to extend these ideas.

BASIC DEFINITIONS

- ***In a particle accelerator the RADIOFREQUENCY SYSTEM is the part of the machine which is devoted to the generation of the accelerating E-field.***

- Due to technical reasons (availability of power sources) and beam dynamics motivations (synchronization with the revolution frequencies of the particle in synchrotrons and cyclotrons) they have been developed mainly in the radio wave region of the e-m spectrum.



www.lbl.gov

TASKS OF THE RF SYSTEM

- ✓ **Accelerate the beam to higher energy**
  - ✓ *Ex. Linacs, synchrotrons*
- ✓ **Compensate the losses due to synchrotron radiation**
  - ✓ *Ex. Electron storage rings*
- ✓ **Provide a stable energy bucket to ensure a long lifetime**

TASKS OF THE RF SYSTEM

Accelerate the beam to higher energy

- ✓ **LINAC**
  - ✓ FERMI linac: the electron beam is accelerated up to 1.5 GeV
  - ✓ ESS linac; the proton beam will be accelerated to 2 GeV
  - ✓ ……….
- ✓ **SYNCHROTRONS**
  - ✓ Elettra booster: the electron beam is accelerated from 100 MeV to 2.4 GeV
  - ✓ In SPS protons are accelerated up to 450 GeV ,then in LHC they reach 4 TeV (per beam)
  - ✓ ……….
- ✓ **CYCLOTRONS**
  - ✓ In the PSI ring cyclotron protons reach 590 MeV.
  - ✓ …………..

TASKS OF THE RF SYSTEM

Compensate the losses du to synchrotron radiation

- ✓ Electromagnetic radiation is emitted by charged particles when accelerated in a curved path.

For a bending magnet: $Uo = 88.5\ E^4/\rho$

- ✓ EXAMPLE- Elettra light source t 2 GeV
  - ✓ Energy loss due to the bending magnet is 255.7 keV/turn.
  - ✓ To this we should add the losses in the insertion devices, which amount to 110.8 keV/turn
  - ✓ For a 330 mA beam this means 121 kW
  - ✓ Without RF the beam is lost in less than 2 msec.

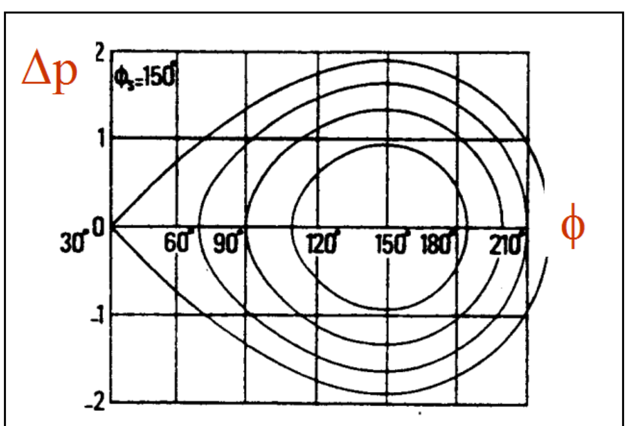
- ✓ **The RF system must provide the power for the energy loss, otherwise the beam is rapidly lost**

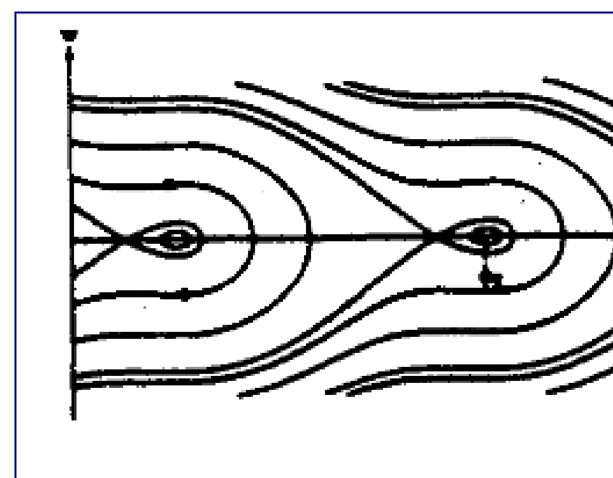
TASKS OF THE RF SYSTEM

Provide a stable energy bucket to ensure a long lifetime

- ✓ RF acceptance is defined as the maximum energy deviation for which the synchrotron oscillation remains stable
- ✓ To ensure stability of longitudinal stability we need some **overvoltage factor;**

  $q=V_{cav/}/U_{losses}$



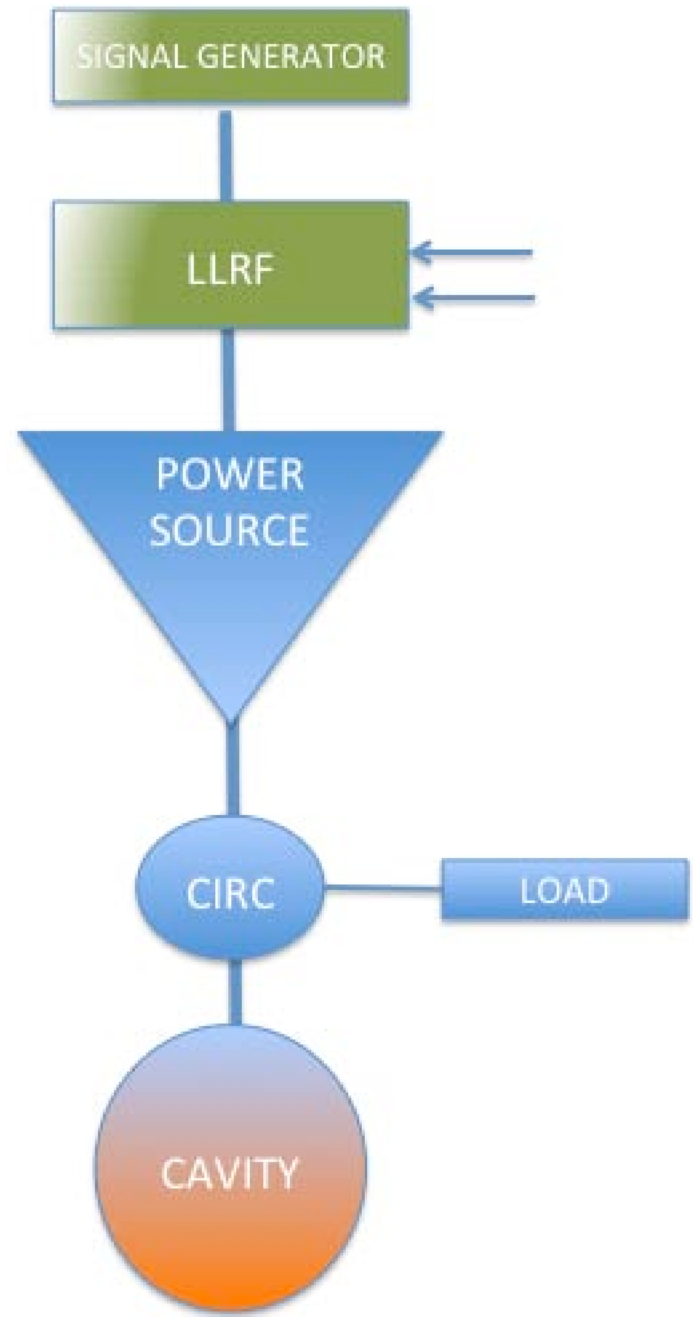


BUILDING BLOCKS

BUILDING BLOCKS

CAVITY

- ✓ This is where interaction with the beam takes place.
- ✓ Accelerates the beam
- ✓ Losses recovery
- ✓ Travelling or standing wave
- ✓ Single or multicell
- ✓ Normal or superconducting



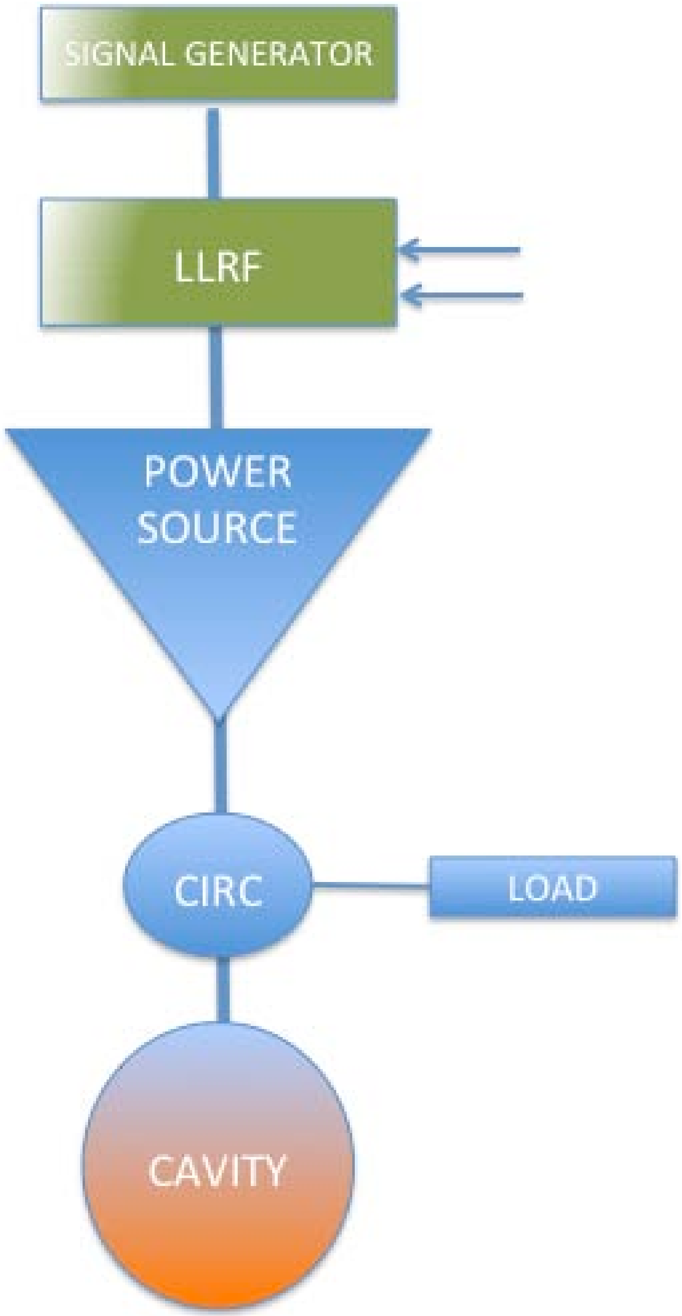
BUILDING BLOCKS

POWER SOURCE

- ✓ Amplification of the driving signal to high level
- ✓ Tubes, solid state
- ✓ ……………

POWER TRANSMISSION

- ✓ Transports RF power
- ✓ Waveguide, coaxial
- ✓ Special components (circulators, directional couplers, loads, etc.)
- ✓ ……………



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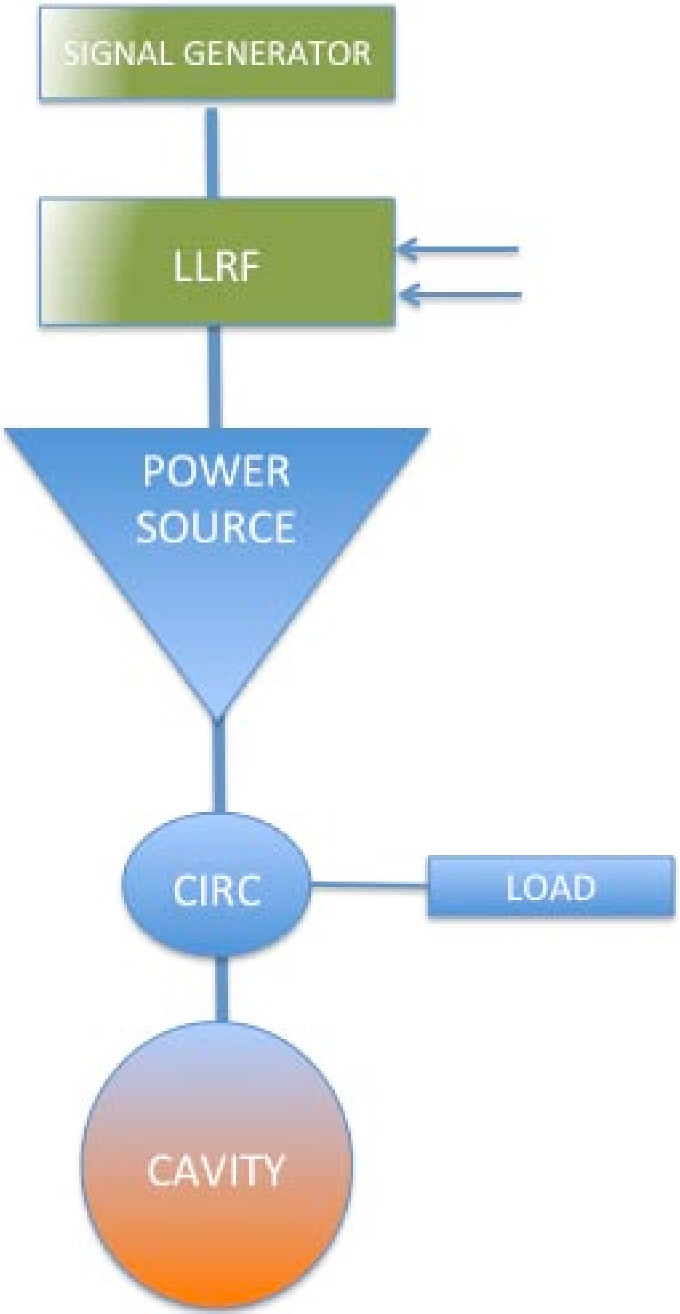
BUILDING BLOCKS



SIGNAL GENERATOR

- ✓ synthesized oscillators
- ✓ VCOs
- ✓ Laser to voltage converters

LOW LEVEL RF (LLRF)

- ✓ Amplitude and phase setting
- ✓ Amplitude and phase stabilization
- ✓ Tuning control
- ✓ Beam loading compensation
- ✓ Feedbacks

PRACTICAL POINTS

RF FREQUENCY

- ✓ RF frequencies in use in RF accelerators span from tens of MHz to tens of GHz
- ✓ Depends on machine type and requirements
- ✓ Depends on availability of sources

DUTY CYCLE

- ✓ RF system can operate continuously (also called CW=continuous wave), or pulsed

POWER LEVELS

- ✓ Powers sources up up to ~ 2 MW rms and ~ 100 MW pulsed

TECHNOLOGIES

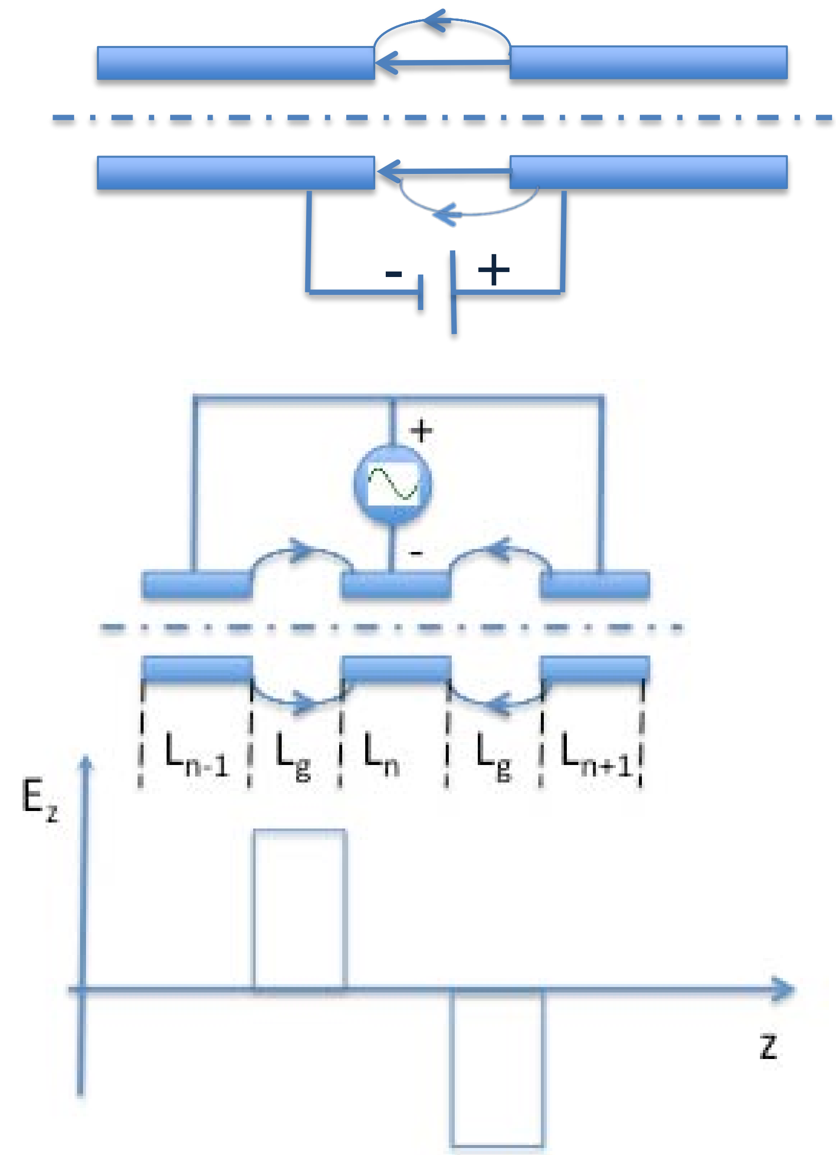
- ✓ Electromagnetism
- ✓ High voltage
- ✓ Vacuum
- ✓ Cooling
- ✓ Superconductivity
- ✓ Cryogenics
- ✓ Material science
- ✓ ………….

ACCELERATING STRUCTURES

ACCELERATING GAP

- ✓ An accelerating gap is the volume between two metallic (good conductors) tubes with the same axis. If the tubes are connected to a dc voltage, the field is as indicated.
- ✓ A negative particle coming from the ”negative” electrode gains energy passing through the gap.

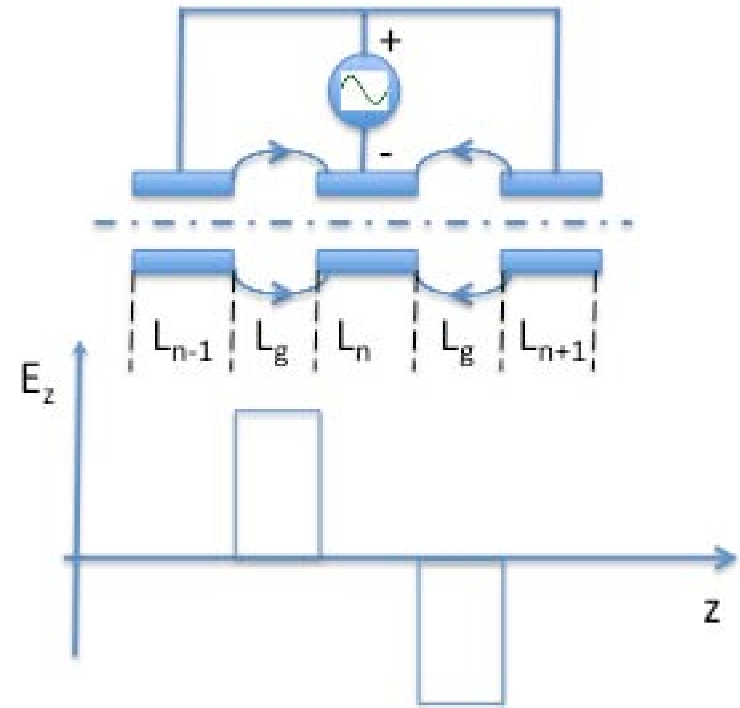
- ✓ If we assemble many gap in series and excite them properly with an AC voltage generator we obtain an electromagnetic linac (WIDEROE)



DRIFT TUBE

- ✓ Beam is accelerated when crossing the gap drift tubes
- ✓ If a particle that transit the gap has to be accelerated, the drift tube length is related to the particle velocity by the synchronism condition:

$$L_n = \frac{1}{2}\beta_n\lambda_{rf} \quad where\ \beta = v/c$$



- ✓ Clearly as the velocity increases the drift tube become inconveniently long, unless the frequency can be increased.
- ✓ But: at high frequency an open drift tube structure become very lossy
- ✓ The natural evolution of the drift tubes was represented by high frequency, field distribute structures like resonant cavities or disk loaded waveguides.

THE TRANSIT TIME EFFECT

A charged particle passing through a gap experiences a field that changes with time and position

$$E(t) = E_0 \cos(2\pi t / T + \phi)$$

Field seen by the particle when crossing the reference plane (Note we assumed uniform field along the gap)

$$\Delta V = \int_{-g/2}^{+g/2} E(t)\, dz$$

Voltage gain for a particle crossing the gap of length g

If the energy gain is small with respect to the energy of the particle, we can assume: $z = v_p t$, where v_p is the average speed of the particle and we have:

$$\Delta V = E_0 g \cos\phi \frac{\sin\theta/2}{\theta/2}$$

$$\theta = 2\pi \frac{g}{v_p}$$

The **transit time factor** is the reduction factor that takes into account the fact that the particle crosses the gap in a finite time

$$T = \frac{\Delta V}{V} = \frac{\sin\theta/2}{\theta/2}$$

MAXWELL EQUATIONS

$$\nabla \bullet \vec{D} = \rho_V$$

$$\nabla \bullet \vec{B} = 0$$

$$\nabla \times \vec{E} = -\frac{d\vec{B}}{dt}$$

$$\nabla \times \vec{H} = J + \frac{d\vec{D}}{dt}$$

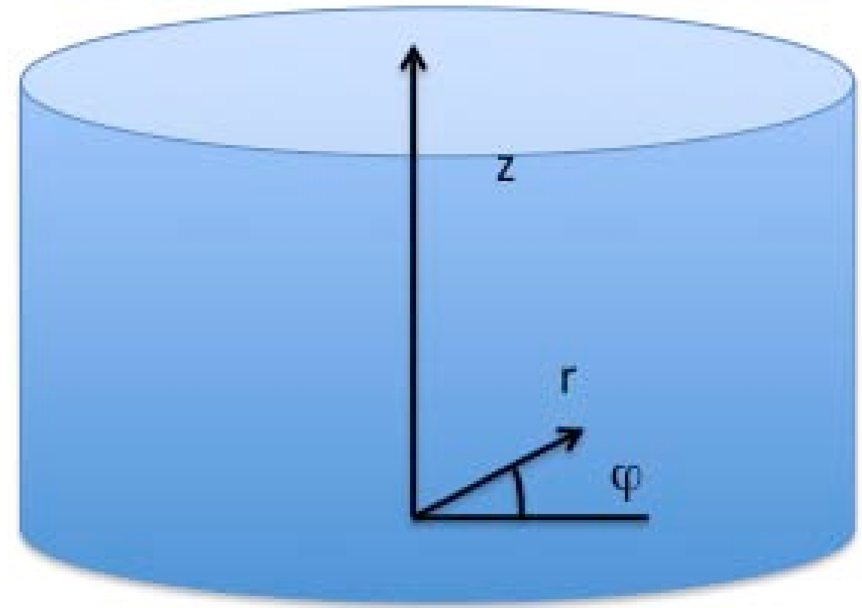
$\vec{E}$	*electric field (V/m)*
$\vec{D} = \varepsilon_0 \varepsilon_r \vec{E}$	*dielectric displacement* (As/m^2)
$\vec{B}$	*magnetic induction*
$\vec{H} = \frac{1}{\mu_0 \mu_r} \vec{B}$	*magnetic field strength/field intensity (A/m)*
$\vec{J} = k\vec{E}$	*electric current density* (A/m^2)
$\frac{d}{dt}\vec{D}$	*displacement current* (A/m^2)
$\varepsilon_0 = 8.85 \cdot 10^{-12} \frac{F}{m}$	*electric field constant*
ε_r	*relative dielectric constant*
$\mu_0 = 4\pi \cdot 10^{-7} \frac{H}{m}$	*magnetic field constant*
μ_r	*relative permeability constant*
k	*electrical conductivity (S/m)*

$$\varepsilon = \varepsilon_0 \varepsilon_r$$

$$\mu = \mu_0 \mu_r$$

RESONANT CAVITY

- ✓ Closed volume where the e.m. fields can only exists in the form of particular spatial conformations (resonant modes) rigidly oscillating at some characteristic frequencies.(standing wave resonators).
- ✓ The resonant cavity modes are the solutions of the Maxwell equations inside closed volumes surrounded by perfectly conducting walls.

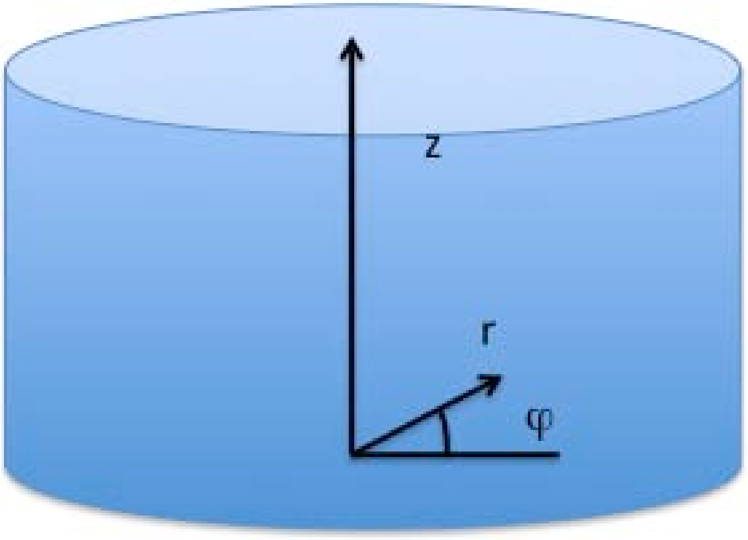


- ✓ The solution is represented by a discrete set of eigenfunctions $\vec{E}_n(\vec{r})$ and their associated eigenvalues $k_n = \omega_n/c$
- ✓ The magnetic field eigenfunctions can be obtained form the Maxwell 3rd equation.
- ✓ The $\vec{E}_n(\vec{r})$ functions are the cavity modes, each one resonating at a specific frequency ω_n.

RESONANT CAVITY

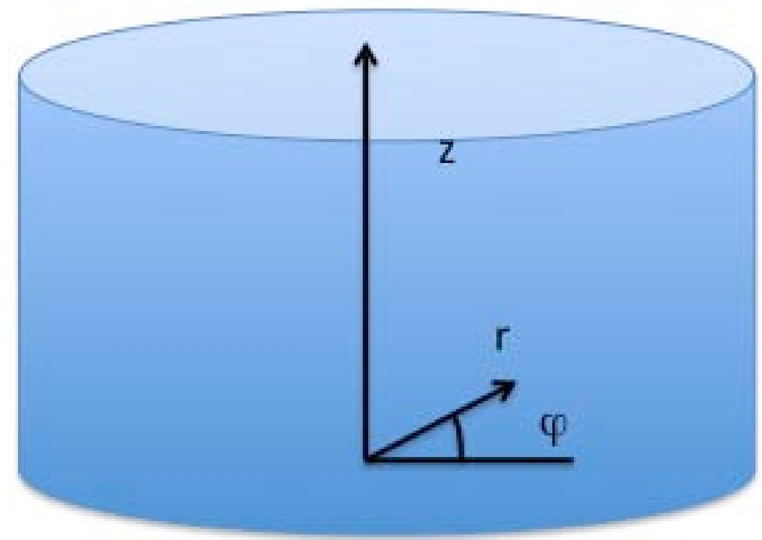
- The eigenfunctions are a linear independent base, so the actual fields can be always be represented by a linear superposition of the cavity modes.
- The definition of the modes is generally
  - TM_{mnp} or E_{mnp} modes: magnetic field only in transverse direction
  - TE_{mnp} or H_{mnp} modes: electric field only in transverse direction

- In cylindrical coordinates:
  - **m** = number of full-period variation of the fields components in the azimuthal direction
  - **n** = number of zero-crossing of the longitudinal field components in the radial direction
  - **p** = number of half-period variations of the fields components in the longitudinal direction



PILL BOX CAVITY

- ✓ Cylindrical empty volume limited by perfect conducting walls
- ✓ Assumption $\rho = J = 0$ inside the volume
- ✓ The Maxwell equation can be solved in cylindrical coordinates.
- ✓ The simplest solution is the TM_{010} mode:
  - ✓ Longitudinal electric field and transverse magnetic fields
  - ✓ No field dependence on z and ϕ
  - ✓ Frequency is only determined by the radius.



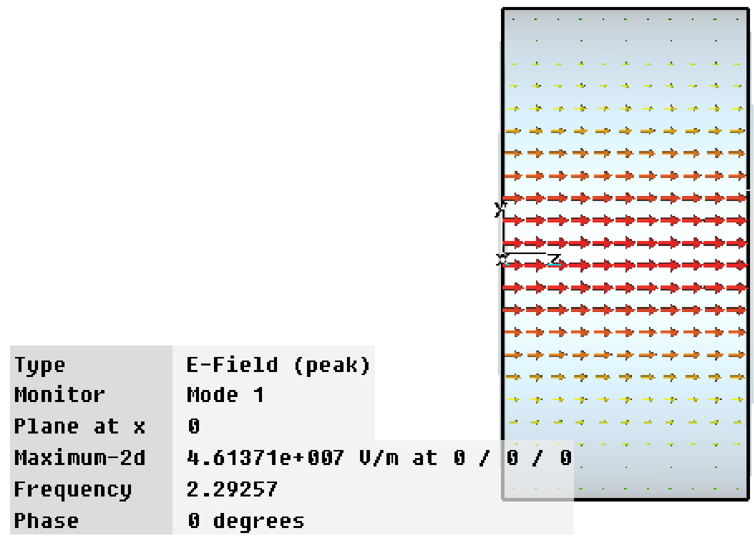
$$E_r = 0$$

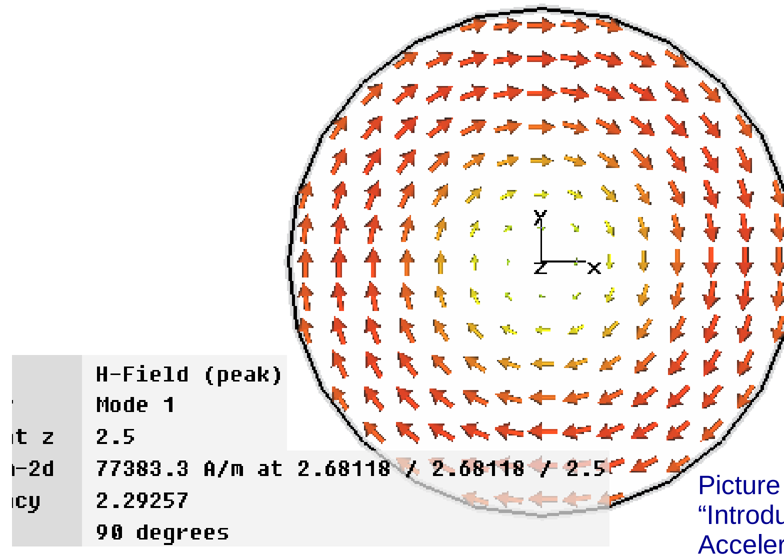
$$E_z = E_0 J_0(k_r r)\cos(\omega t) \qquad TM_{010}\ mode$$

$$B_\varphi = -\frac{E_0}{c} J_1(k_r r)\sin(\omega t)$$

$$\omega_0 = k_r c = \frac{2.405 \cdot c}{R_{cav}} \qquad angular\ frequency$$

PILL BOX CAVITY





Picture from G. Burt., “Introduction to RF for Particle Accelerators”, Lancaster University

- ✓ If one makes a hole on each side of the cavity, then particles can travel along the cavity and be accelerated.
- ✓ However real geometries adopted differ from the pill-box case:
  - ✓ To increase accelerating efficiency one can introduce nose cones, as in many normal conducting cavities
  - ✓ Geometry are smoothed (bell-shape) to avoid multipacting as in sc cavities or in the Elettra type nc cavity.
- ✓ Frequency and modes are calculated by means of e.m. simulation codes (SuperFISH, CST microwave, HFSS,…)

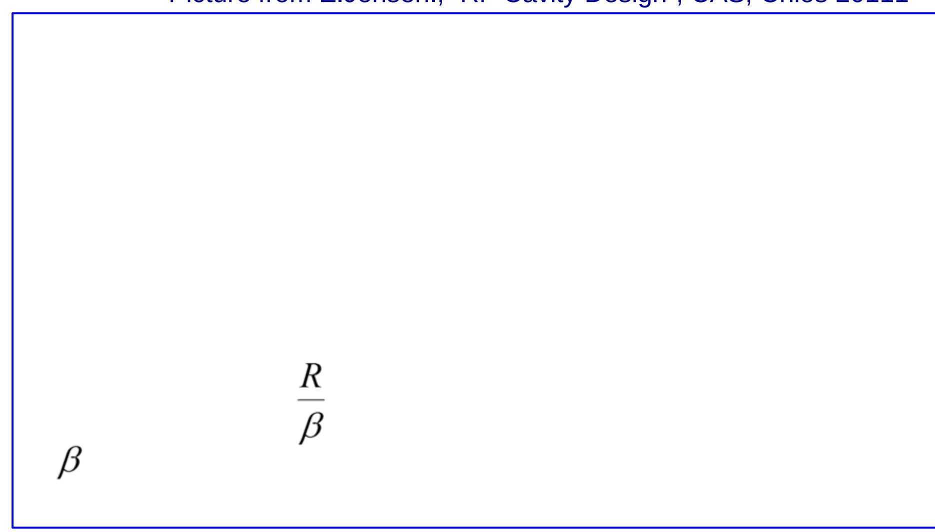
REAL CAVITY

- ✓ From ideal to real cavities we have to taken into account:
  - ✓ The mechanical boundaries of the cavities are non-perfect conductors and (eventually) non perfect dielectrics.
  - ✓ The continuity of the mechanical boundary is interrupted by the holes that are needed for coupling and monitoring.
- ✓ These perturbations introduce losses, so that a certain amount of power should be introduced inside the cavity to keep the field at the the desired level. If this is not done cavity field would decay exponentially.

CAVITY EQUIVALENT CIRCUIT

- ✓ A single mode of a resonant cavity can be represented as a simple RLC circuit
- ✓ In fact equivalent circuits have been proven to accurately model couplers, cavity coupling, microphonics, beam loading and field amplitudes in multicell cavities.

Picture from E.Jensen., "RF Cavity Design", CAS, Chios 20111



- ✓ These simple circuit equations can now be used to calculate the cavity parameters

FIGURES OF MERIT

gle cell:

$$50 \div 100\,\Omega$$

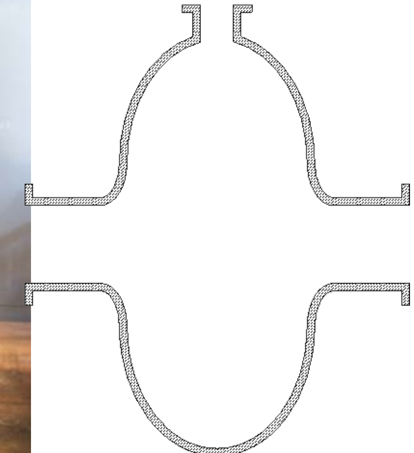
From A. Gallo, "RF Systems", CAS, Varna 2010

NORMAL CONDUCTING SUPERCONDUCTING

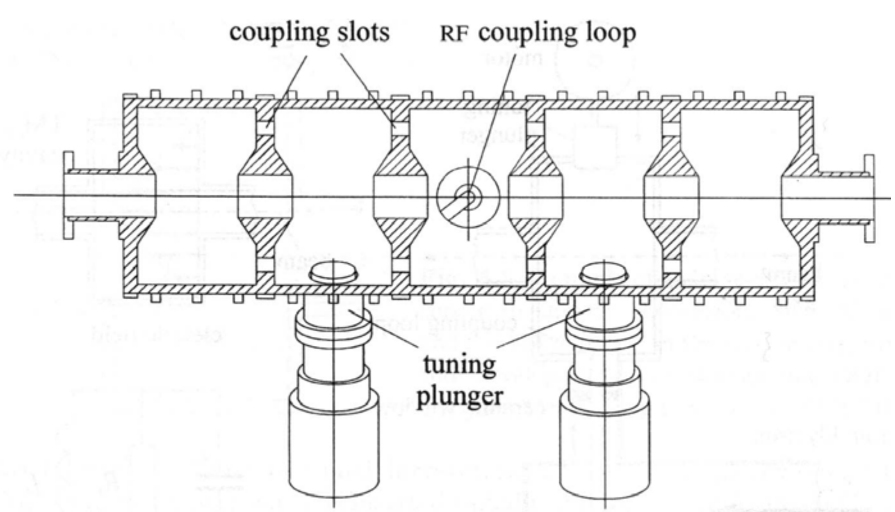
- ✓ Cavities can be wither normal conducting or superconduting.
- ✓ Choice depends on the specific application.
- ✓ Although there is no a definitive rule for the choice, in general:
  - ✓ Normal conducting
    - ✓ *Less infrastructure*
    - ✓ *Simpler technology*
    - ✓ *Simpler tuning*
    - ✓ *Higher RF power needs*
    - ✓ *Thermal problems*
    - ✓ *Lower gradients (i.e. more cavities needed for the same total voltage).*
  - ✓ Super conducting
    - ✓ *No thermal problems*
    - ✓ *Less RF power, but do not forget the cryogenics*
    - ✓ *Larger aperture*
    - ✓ *Multipacting*
    - ✓ *Cryogenic system required*
    - ✓ *Complicated cavity fabrication*
    - ✓ *Sensitive cavities*

SINGLE CELL MULTICELL

- ✓ To increase acceleration efficiency, coupled structures can be used.
- ✓ But also in this case there is no universal recipe and the choice depends on the application, for example dangerous HOMs can be more easily damped in single cell cavities.
- ✓ Phase relation between the gap is important: 0, …, π/2…,π modes, following the phase advance per cell of the waveguide modes



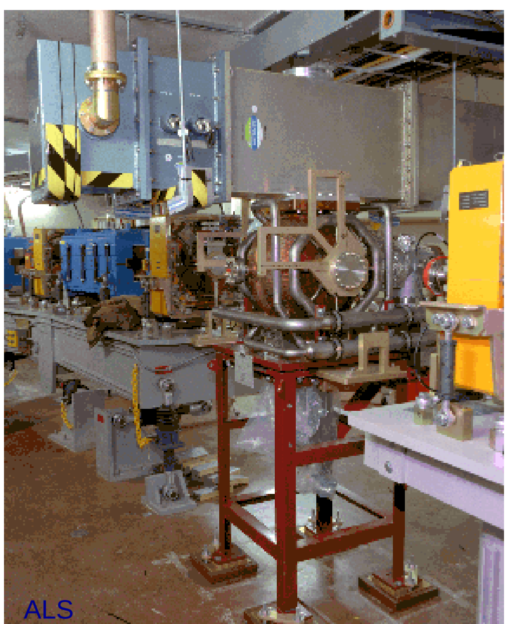
Elettra cavity



Petra cavity

COUPLING

- **INPUT POWER COUPLERS**: to feed the cavity with RF power
- **RF PICK-UPs**: to probe the field inside
- **TYPE OF COUPLING**
  - **MAGNETIC: (LOOPS)**: The magnetic field of the mode we want to excite in the cavity has a component in common with a loop connecting the inner and outer conuctors of a transmission line.
  - **ELECTRIC COUPLING (ANTENNAS)**: the inner conductor of a coaxial lines couples with the electric field of the mode of the cavity.
  - **WAVEGUIDE**: the cavity fields are coupled to an external waveguide through a hole or a slot in the cavity walls.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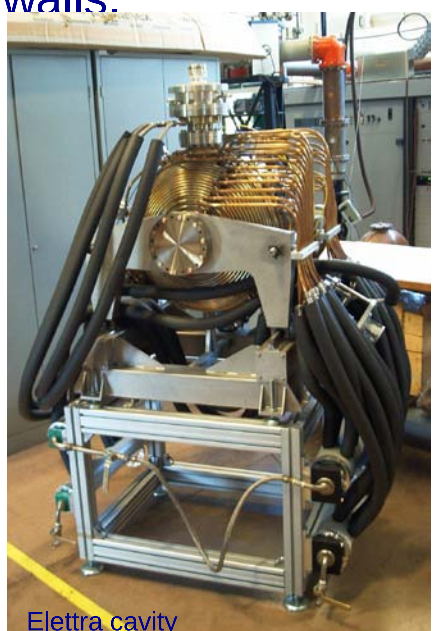

Elettra cavity

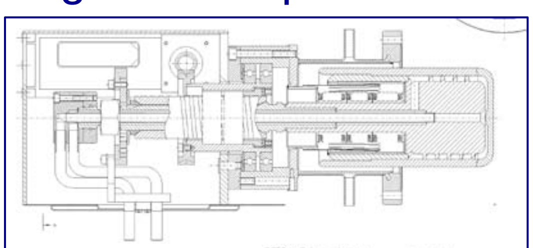
TUNING

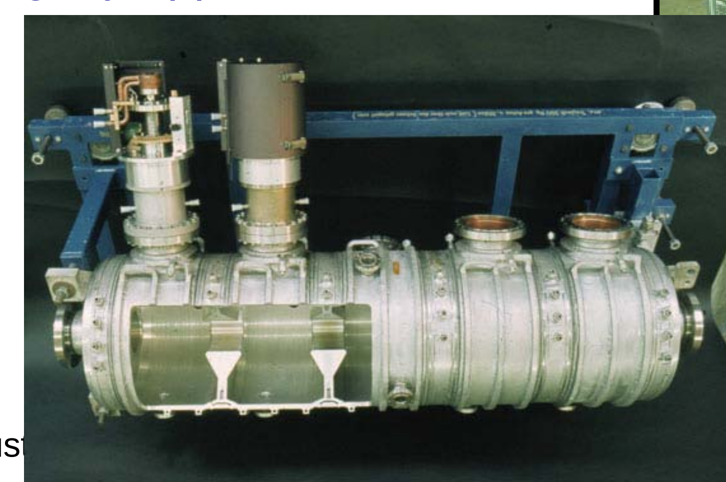
- ✓ Cavity resonant frequencies are affected by different reasons, for example by thermal drifts in normal conducting cavities or by pressure variations in the cryogenic bath in the superconducting case.
- ✓ Cavity should be kept at the required frequency during operation.
- ✓ Cavity frequency control is normally obtained by means of small deformations of the cavity volume.

SLATER THEOREM

$$\frac{\Delta\omega}{\omega} = \frac{\int_{\Delta V} (\mu H^2 - \varepsilon E^2 \, dV}{\int_{\Delta V} (\mu H^2 + \varepsilon E^2 \, dV} = \frac{\int_{\Delta V} (\mu H^2 - \varepsilon E^2 \, dV}{4U}$$

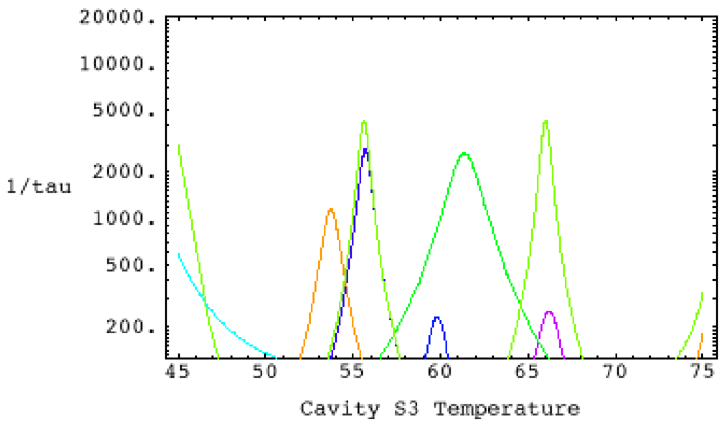
- ✓ **PRACTICAL TUNING MECHANISMS**
  - ✓ Deformation by pushing/stretching by application of axial forces
  - ✓ Plungers
  - ✓ Cooling fluid temperatures

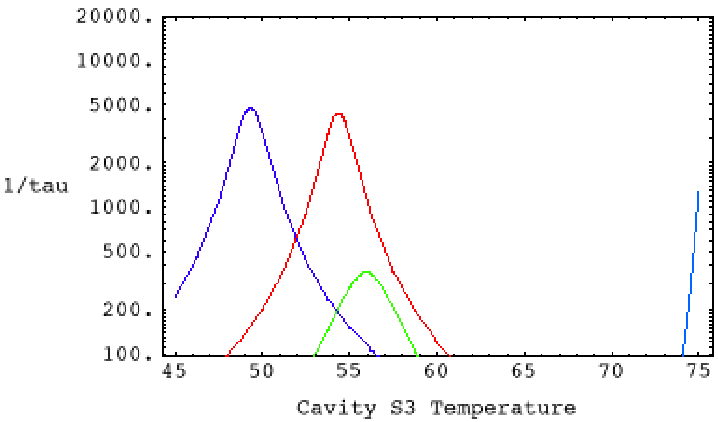




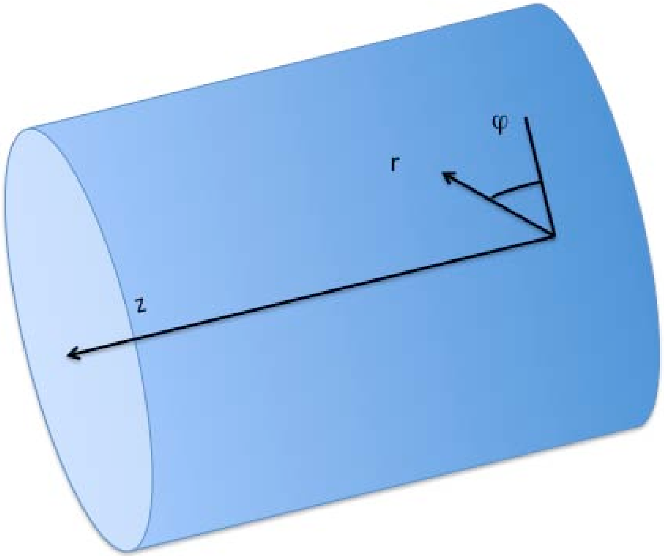
HOM

- ✓ Higher order modes (HOM) can be excited in the cavity by the beam passing into it.
- ✓ HOM can be detrimental to the stability of the beam and should be avoided.
- ✓ Some techniques:
  - ✓ Temperature tuning in nc cavities (es. Elettra cavities).
  - ✓ Dedicated HOM suppressors.
  - ✓ Waveguide dampers (es. PEPII, ALBA)
  - ✓ Beampipe dampers
  - ✓ Longitudinal and transverse feedbacks
  - ✓ ………….





CYLINDRICAL WAVEGUIDE



- ✓ Uniform waveguide: a dielectric volume limited by conducting cylindrical walls
- ✓ For this case we can solve the Maxwell equations in cylindrical coordinates
- ✓ The simplest solutions with an axial electric field is the TM_{01} mode, which has radial and longitudinal electric field and azimuthal magnetic field components.

$$E_r = j\frac{k_z}{k_c}E_0 J_1(k_c r)e^{-jk_z z}e^{j\omega t}$$

$$E_z = E_0 J_0(k_c r)e^{-jk_z Z}e^{j\omega t}$$

$$H_\varphi = j\frac{k}{Z_0 k_c}E_0 J_1(k_c r)e^{-jk_z z}e^{j\omega t}$$

TM_{01} in cylindrical coordinates

$k = \frac{2\pi}{\lambda} = \frac{\omega}{c}$ *wave number*

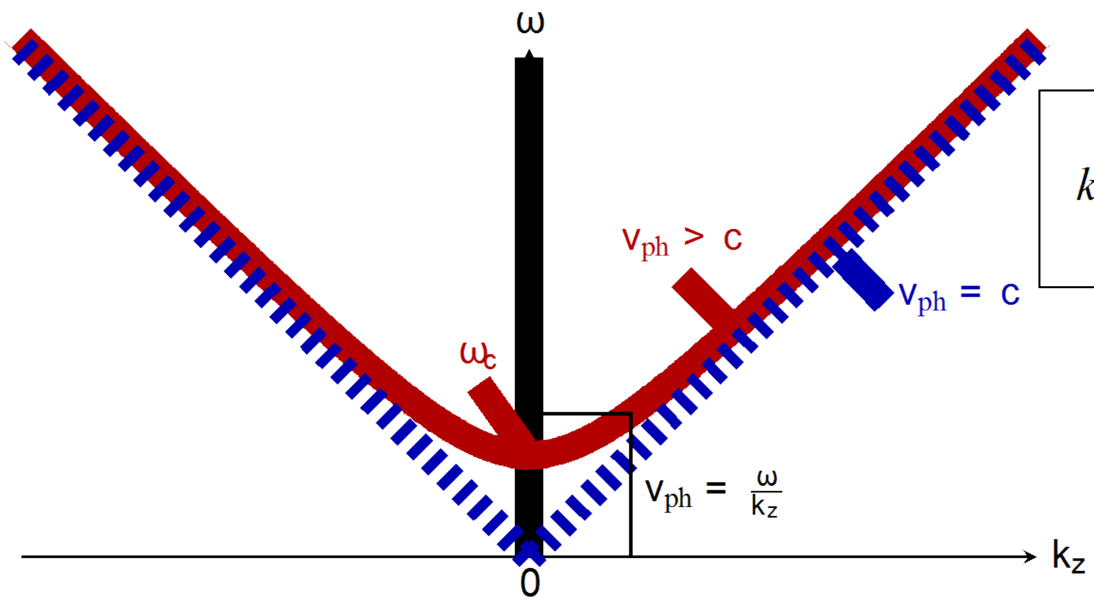
$Z_0 = \sqrt{\frac{\mu_0}{\varepsilon_0}} = 377\Omega$ *free-space impedance*

$\lambda_c \approx 2.61a$ *cut-off wavelength (TM_{01})*

$k_c = \frac{2\pi}{\lambda_c} = \frac{\omega}{c}$ *cut-off wave number*

$k_z^2 = k^2 - k_c^2$ *propagation constant*

CYLINDRICAL WAVEGUIDE



$$k_z^2 = \frac{\omega^2}{v_{ph}^2} = \frac{\omega^2}{c^2} - \frac{\omega_c^2}{c^2} \qquad \textit{dispersion relation}$$

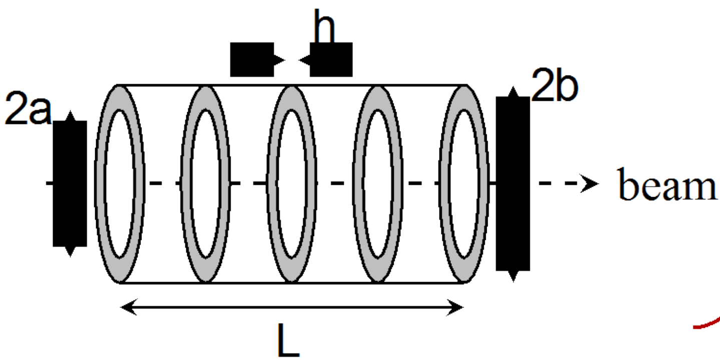
$$v_{ph} = \frac{\omega}{k_z} \qquad \textit{phase velcity}$$

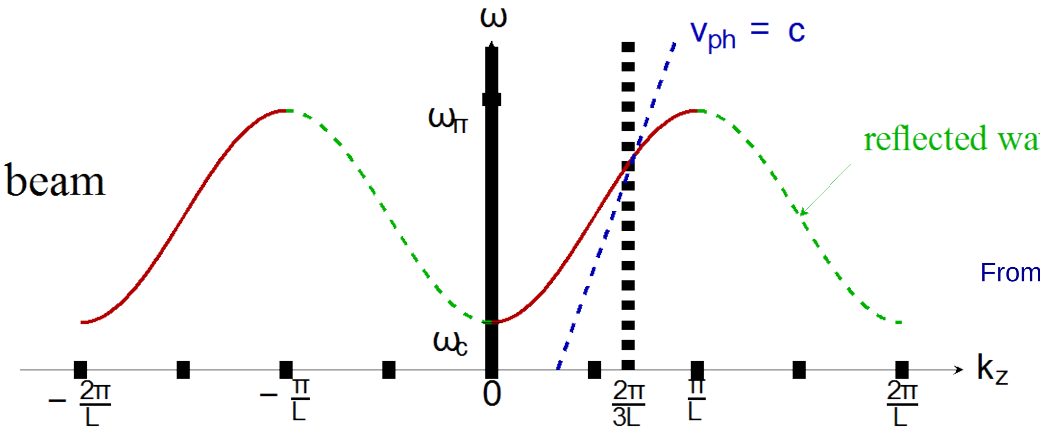
Brillouin diagram for cylindrical waveguide

- ✓ Each frequency correspond to a certain phase velocity
- ✓ Propagation in a waveguide is always possible above the cut-off frequency
- ✓ The phase velocity is always higher than the speed of light
- ✓ It is impossible to accelerate particle in a cylindrical waveguide because synchronism between particle and RF is impossible
- ✓ NB. Information and energy travels at the group velocity $v_{gr}=d\omega/dk_z$ and is always lower than c .

TRAVELLING WAVE STRUCTURE

SOLUTION: Corrugated waveguide – Travelling wave structure





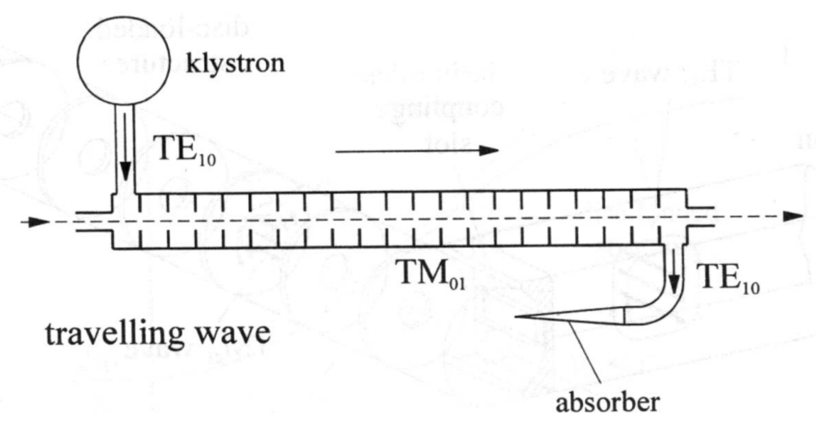
From F. Gerick

$$\omega = \frac{2.405c}{b}\sqrt{1+\kappa(1-\cos(k_z L)e^{-\alpha h})}$$ *dispersion relation for disc-loaded travelling wave structure*

$$\kappa = \frac{4a^3}{3\pi J_1^2(2.405)b^2 L} \langle\langle 1$$

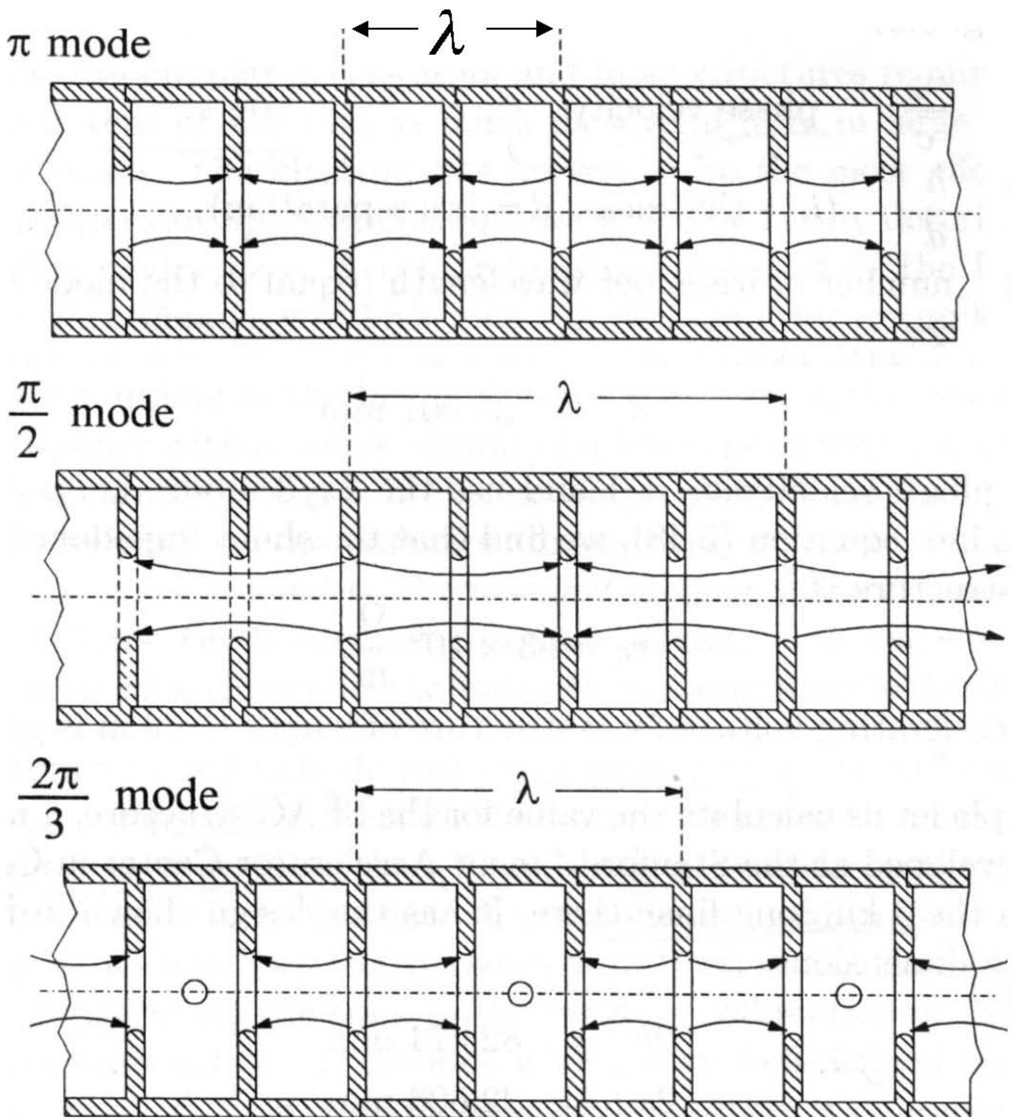
$$\alpha \approx \frac{2.405}{a}$$

✓ Modes with phase velocity below c exist



WAVEGUIDE MODES

✓ Operation mode is defined as the phase difference between adjacent cells



Long initial settling or filling time, not good for pulsed operation.

Small shunt impedance per length.

Common compromise.

From G. Hoffstattetter, USPAS 2010,

EXAMPLES OF TYPES OF CAVITIES

CONSTANT VELOCITY, CONSTANT FREQUENCY

- ✓ **Relativistic particles**
- ✓ **Synchrotrons, linacs**
- ✓ **Electrons from MeV, protons above several GeV**

CHANGING VELOCITY, CONSTANT FREQUENCY

- ✓ **Cyclotrons and low beta ion and proton linacs**

CHANGING VELOCITY, CHANGING FREQUENCY

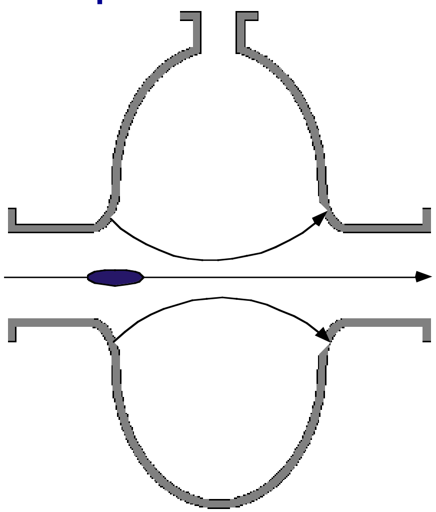
- ✓ **Low beta synchrotrons**
- ✓ **Ferrite cavities**

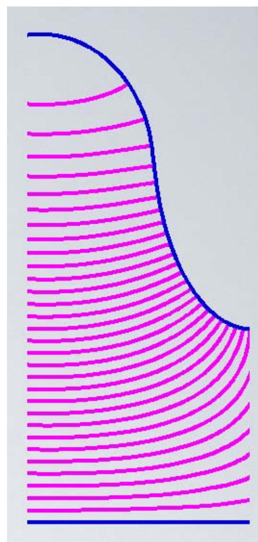
NON ACCELERATING CAVITIES

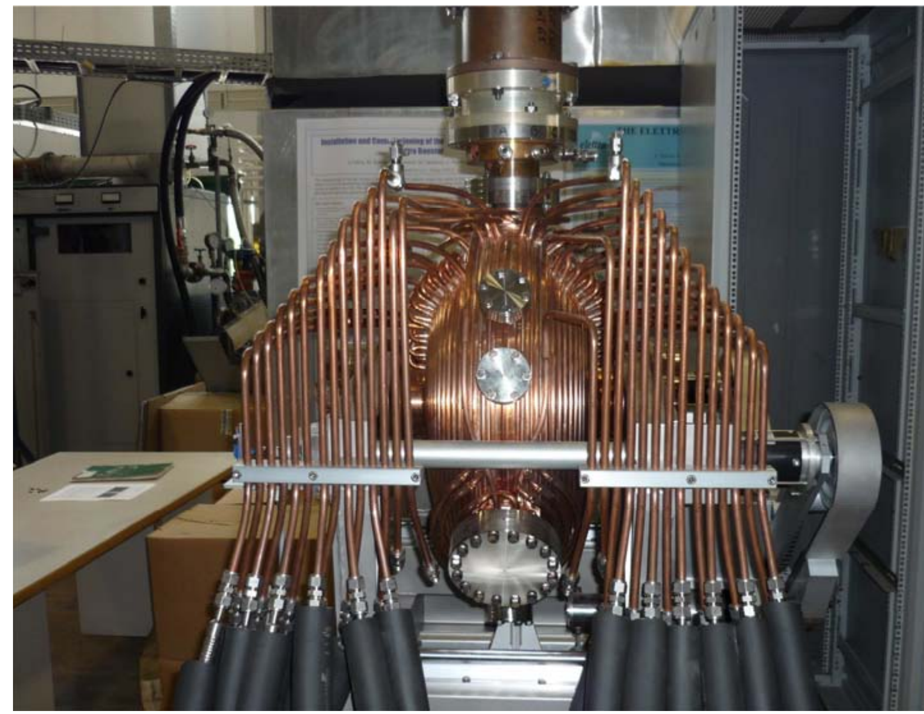
- ✓ **RF Deflectors**
- ✓ **RF bpm**

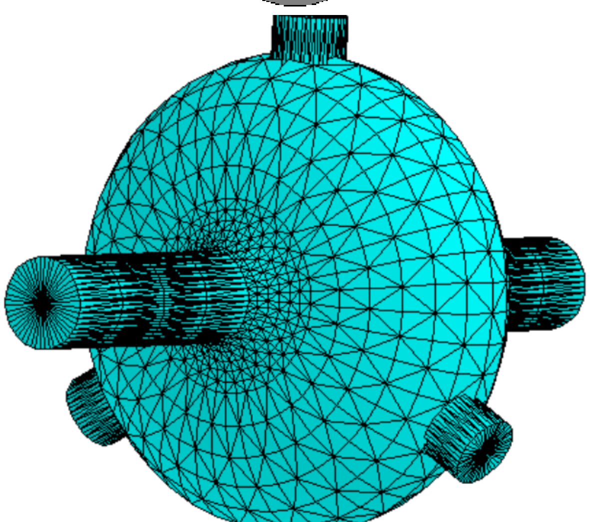
ELETTRA CAVITY

- ✓ Developed for Elettra
- ✓ Used in many synchrotron light sources (Campinas, ANKA, SLS, INDUSII). Now adopted at SESAME.





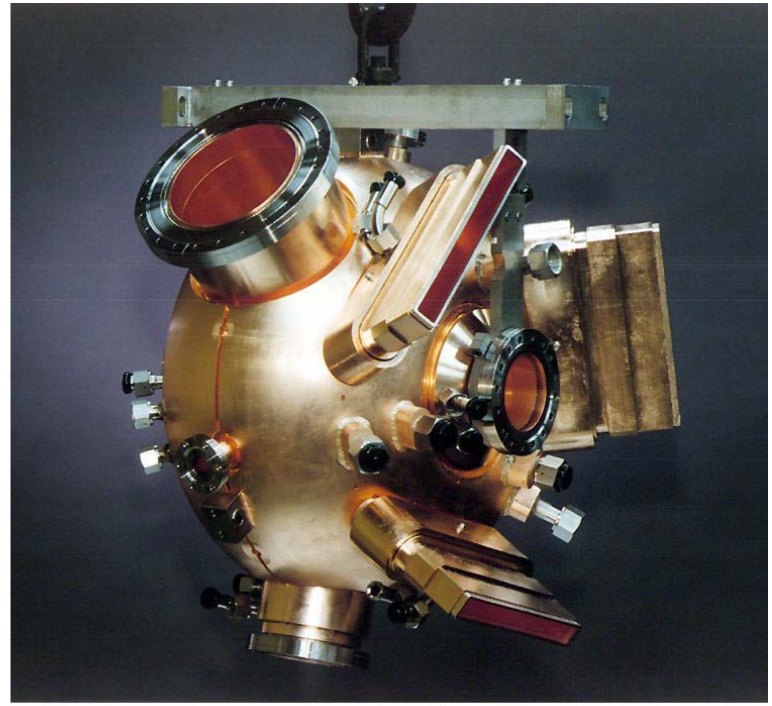




Frequency	500 Mhz
Accelerating voltage (Transit time corrected)	650 kV
Power losses in copper	≤ 66 kW
Shunt impedance	≥ 3.2 MΩ
Nominal forward power matched	100 kW

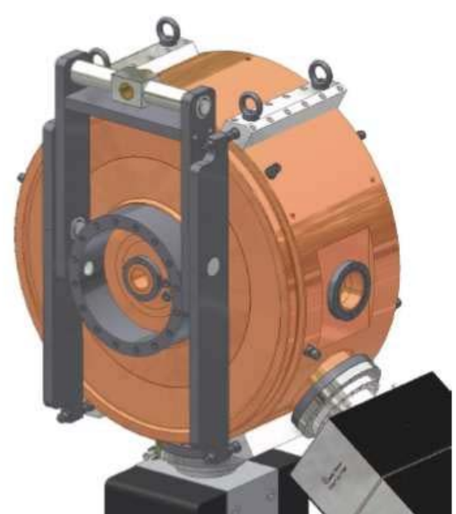
SINGLE CELL CAVITIES

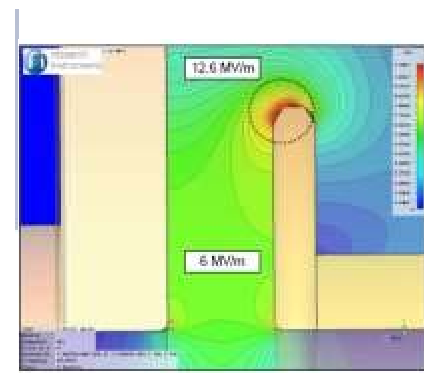
ALBA-500 MHZ



CAV_13 PEP- II RF Cavity 8-19-97

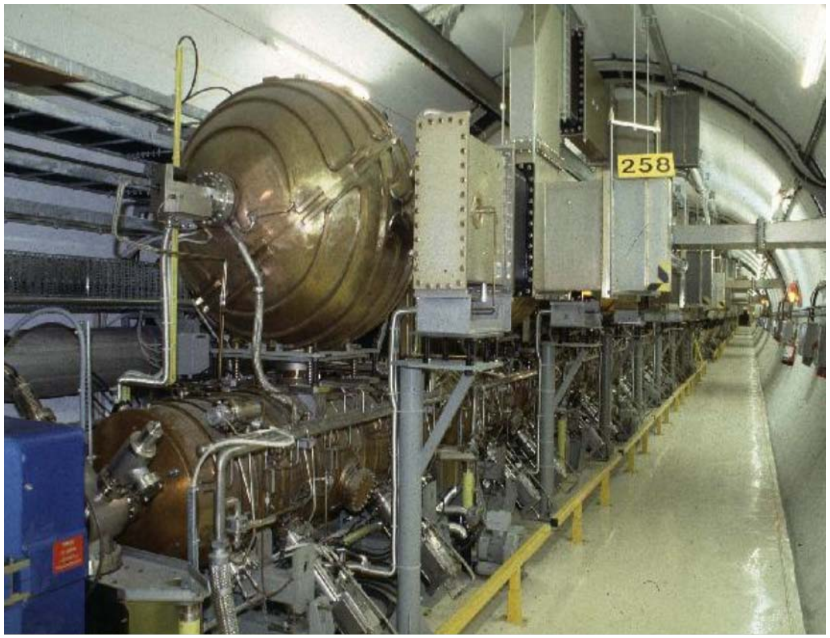
PEP-II -476 MHz



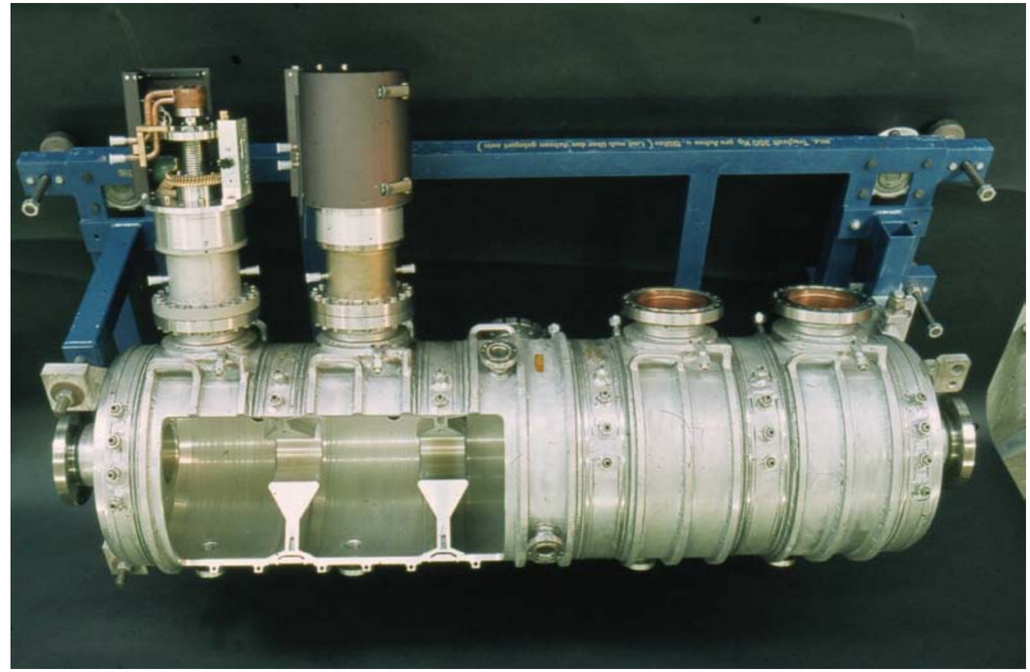


MAX IV -100 MHZ

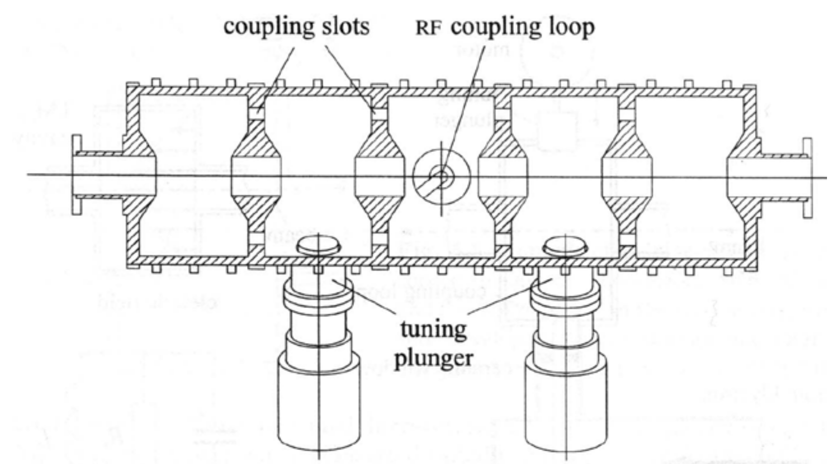
MULTICELL CAVITIES



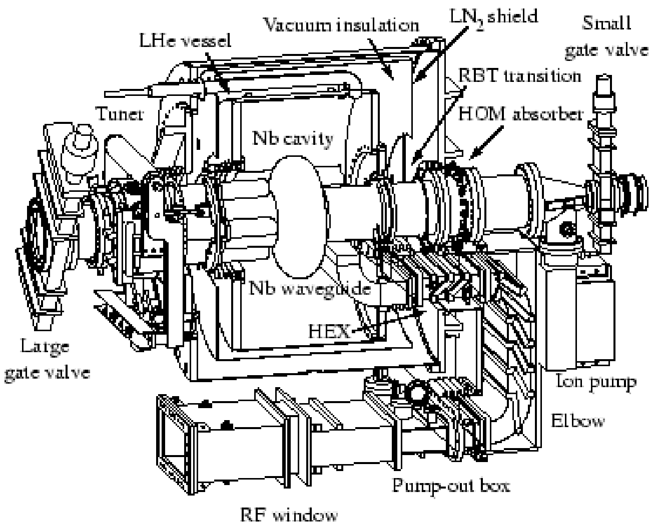
LEP 5 cells Normal conducting + storage cavity

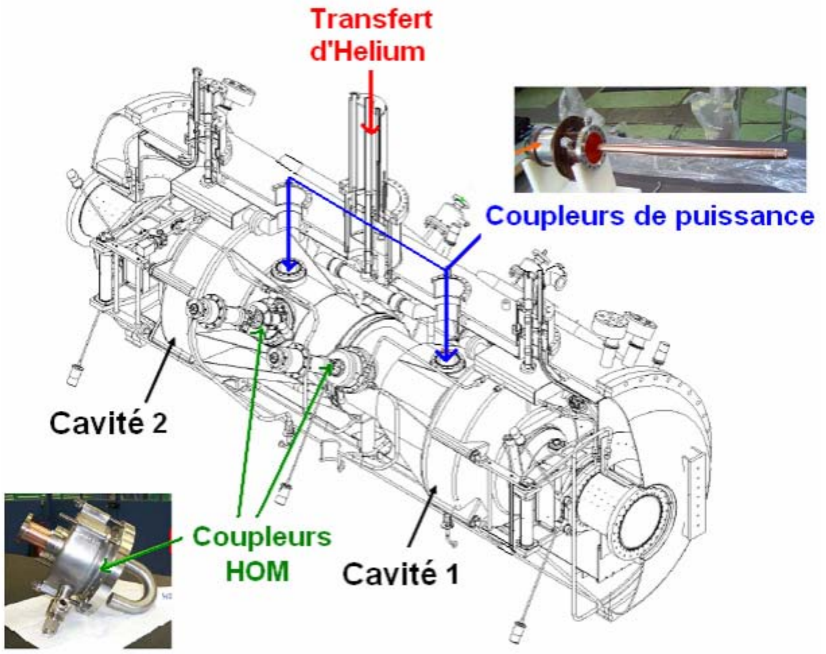


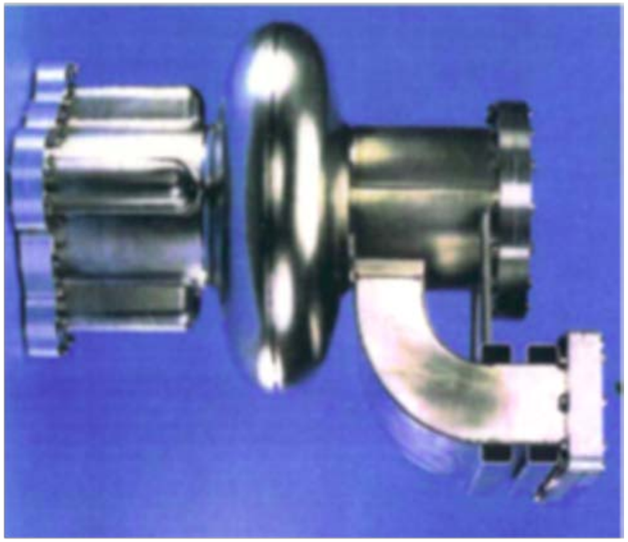
PETRA 5- cells



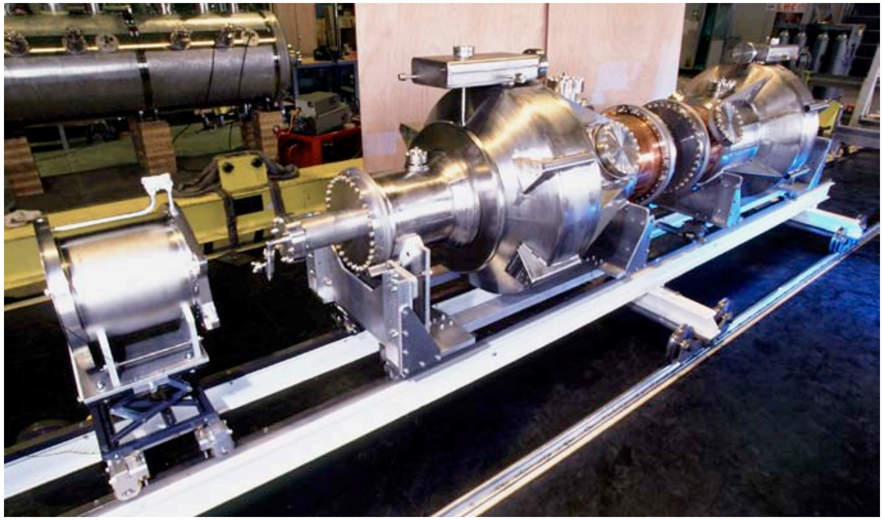
SUPERCONDUCTING CAVITIES





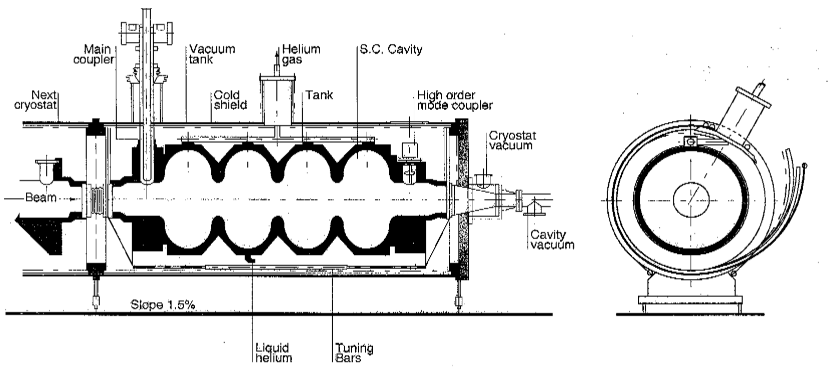


Cornell 500 MHz

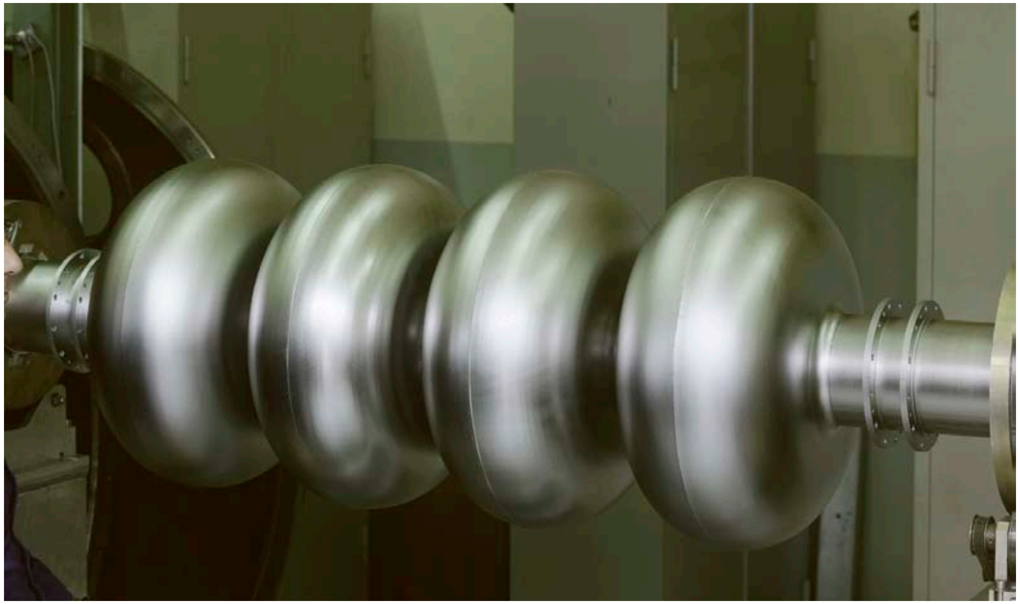


Soleil 352 MHz

SUPERCONDUCTING CAVITIES



LHC 400 MHz



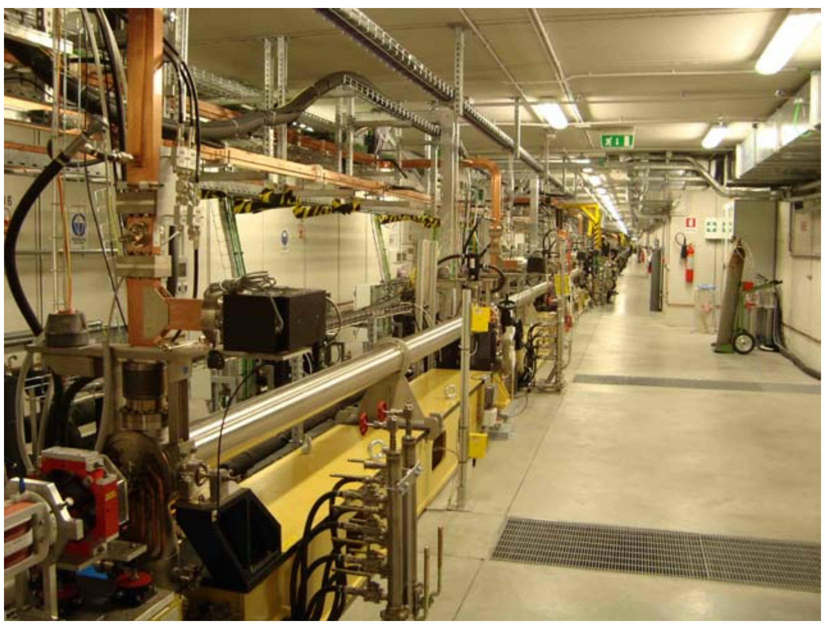
LEP superconducting 352 Mhz

TESLA 1.3 GHZ

TW STRUCTURES

Mode	2π/3 TW on axis coupled
Type	Const. grad
Frequency	2998.010 MHz
Eff. length	4.565 m
Q	14000
Rs	65 MΩ/m
Filling time	1.255 µsec

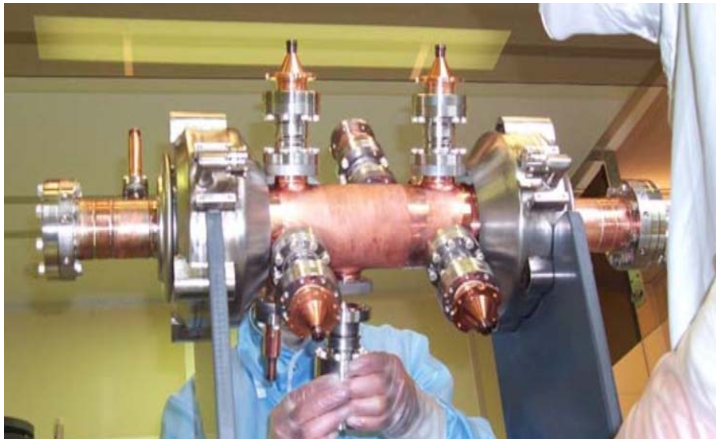
Mode	3π/4 BTW magnet. coupled
Type	Const. grad
Frequency	2998.010 MHz
Eff. length	6.150 m
Q	11700
Rs	71-73 MΩ/m
Filling time	0.603 µsec



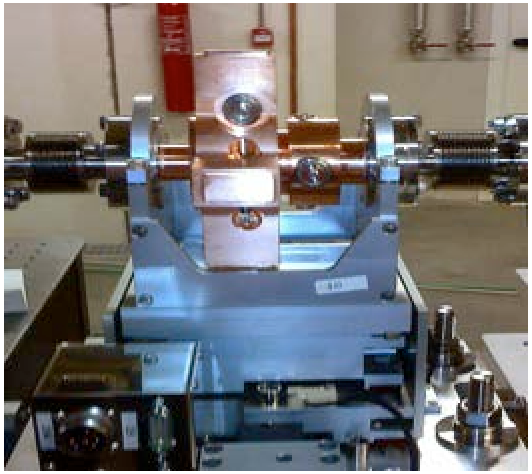
S-band LIL sections in the FERMI linac

S-band BTWsections in the FERMI linac

OTHER EXAMPLES

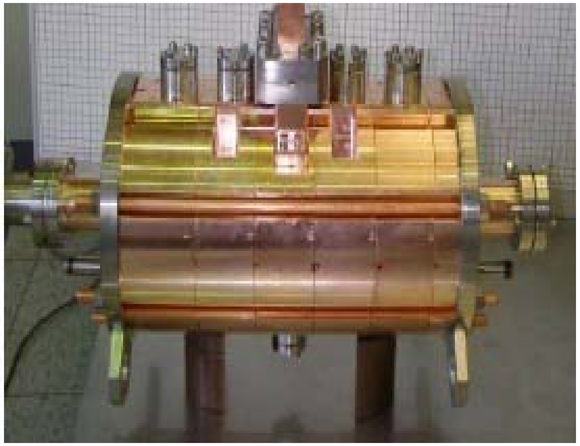


3rd harmonic cavity (Elettra, PSI)



Cavity BPM (FERMI)

High energy deflector (FERMI)



Low energy deflector (FERMI)

MAKING IT WORK

- ✓ RF cavities operate at high e.m. fields and under UHV.
- ✓ The construction and operation require skills on different technology aspects
  - ✓ Mechanical (machining, brazing, etc)
  - ✓ Material science (high purity materials are needed)
  - ✓ Vacuum (cavities operate at UHV, need pumping, bake-out)
  - ✓ Cooling to remove the wasted power on the surface and keep the operating temperature stable.
  - ✓ Cryogenics in case of sc cavities

- ✓ High field operation requires RF conditioning procedures which allows to reach and establish the required operating values in safe operation without breakdowns.

POWER SOURCES

MUCH MORE IN THE "RF POWER GENERATION AND TRANSMISSION FOR PARTICLE ACCELERATORS" LECTURE

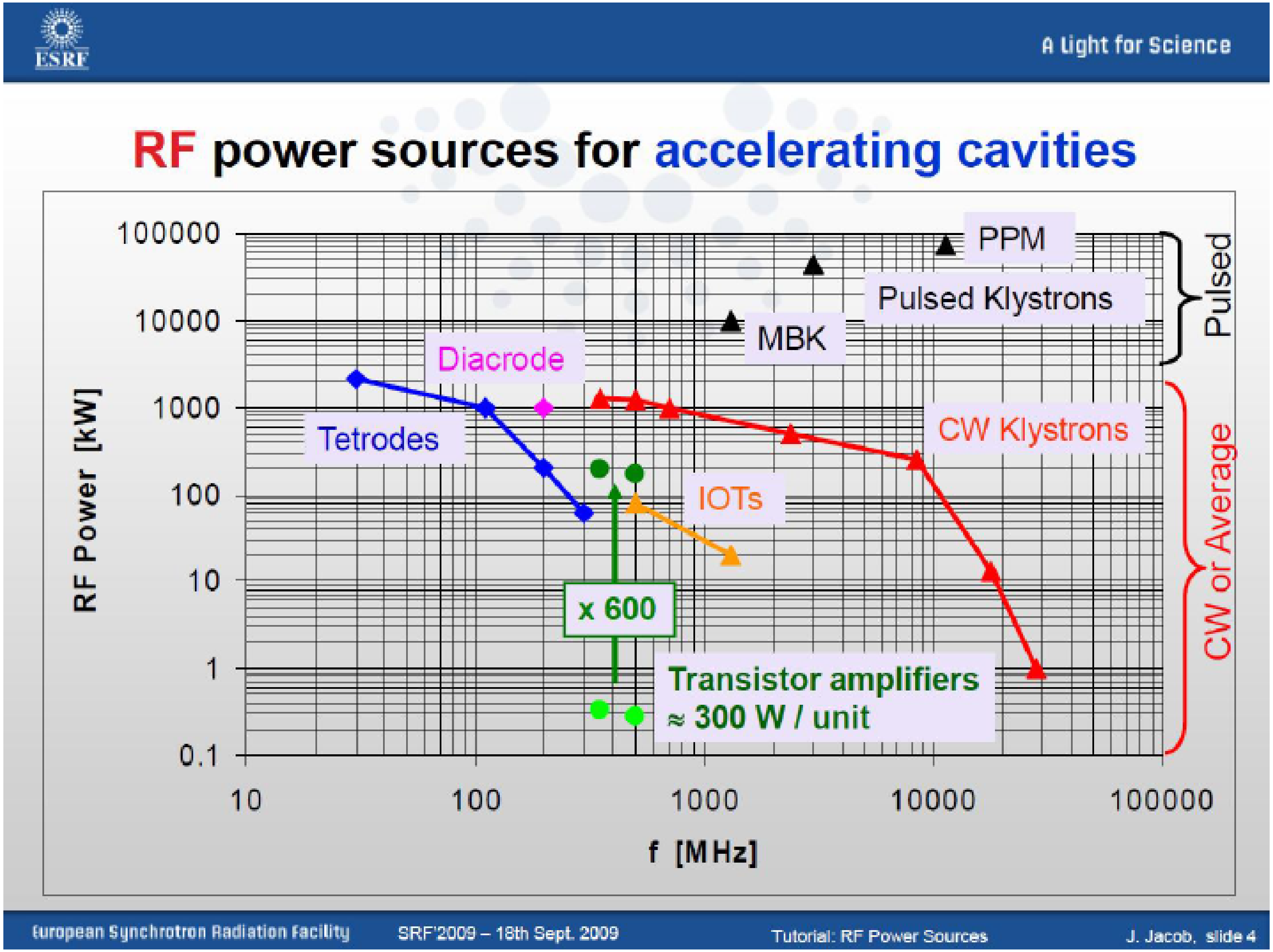
GENERAL POWER SOURCES

- ✓ High power RF is needed is needed for particle accelerators
- ✓ Typical frequency ranges span for tens of MHZ to tens of GHz or higher.
- ✓ Power requirements varies from few kW to few MW in cw (continuous wave) mode operation to up to 150 MW for pulsed sources.

- ✓ **DEFINITION**
- ✓ A power amplifier is the equipment which transforms d.c. electrical input power to RF power amplifying the driving signal provided by the low level RF electronics.
- ✓ If needed, power amplifier can be combined to achieve higher power.

- ✓ **High power sources represent one of the main capital costs both in construction and in operations.**
- ✓ Important concepts: efficiency and gain
- ✓ Other important points: size, weight and maintenance costs.

TECHNOLOGY



- ✓ **Vacuum tubes**
  - ✓ Tetrode
  - ✓ Klystron
  - ✓ IOT
  - ✓ Magnetron
  - ✓ TWT
- ✓ **Solid state**

EXAMPLES

60 kW cw 500 MHz
klystron (E2v 2672BCD))

300 kW cw 500 MHz
klystron (Thales TH22161)

45MW pulsed s-band
klystron (Thales TH2132A)

Tetrode for cw and pulsed
operation (Thales TH595)

80 kW cw 500MHz
IOT (E2V 2130))

EXAMPLES

60 kW cw 500MHz klystron based amplifier at Elettra

150 kW cw 500MHz combined IOTs based amplifier at Elettra

45 MW peak S-band klystron and modulator at FERMI

Solid state amplifier towers at SOLEIL (352 MHZ)

POWER TRANSMISSION

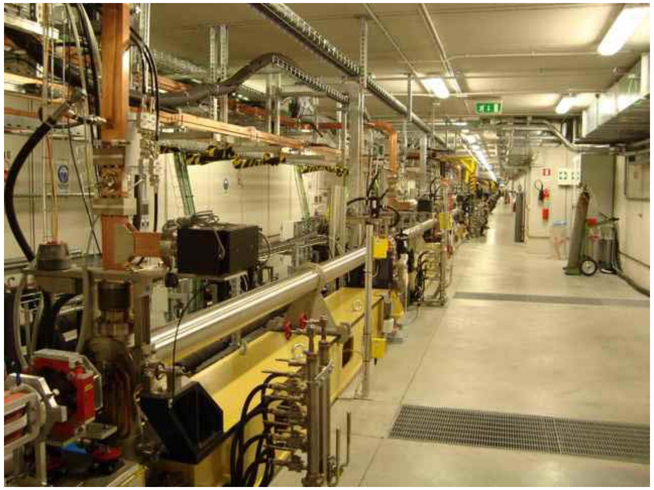
MUCH MORE IN THE "RF POWER GENERATION AND TRANSMISSION FOR PARTICLE ACCELERATORS" LECTURE

GENERAL POWER TRANSMISSION

The power transmission system is the assembly of components that perform the tasks of transporting the RF power from the power source to the cavities.

- ✓ This is usually accomplished by a network of coaxial lines or rigid rectangular waveguides.
- ✓ **The choice depends on the frequency and power levels involved.**
- ✓ **Coaxial lines**
  - ✓ No cut-off
  - ✓ Higher attenuation
  - ✓ Difficult to cool
  - ✓ Typical ranges in use: frequency dc to 10 GHz, power rating example 1 MW at 200 MHz
- ✓ **Waveguides**
  - ✓ Cut-off
  - ✓ Lower attenuation
  - ✓ Easier to cool
  - ✓ Higher frequency
  - ✓ Higher power
  - ✓ Typical ranges in use: frequency 0.32 to 352 GHz, power rating example 150 MW peak at 310 MHz
- ✓ In addition to standard components, also special components are needed, like bends, directional couplers, circulators, loads, etc.

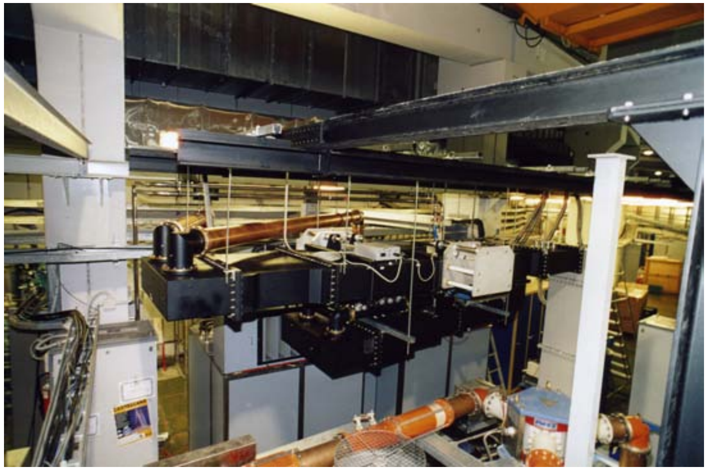
EXAMPLES



Waveguides feeding the S-band
FERMI linac

Circulator, load and coaxial lines
for the 500 MHZ Elettra plants

500 MHz waveguide circulator



Swtichless combiner

LLRF

SCOPE

The low level RF system (LLRF) has the purpose of generating the driving signal provided to the high power amplifier with the correct amplitude and phase.

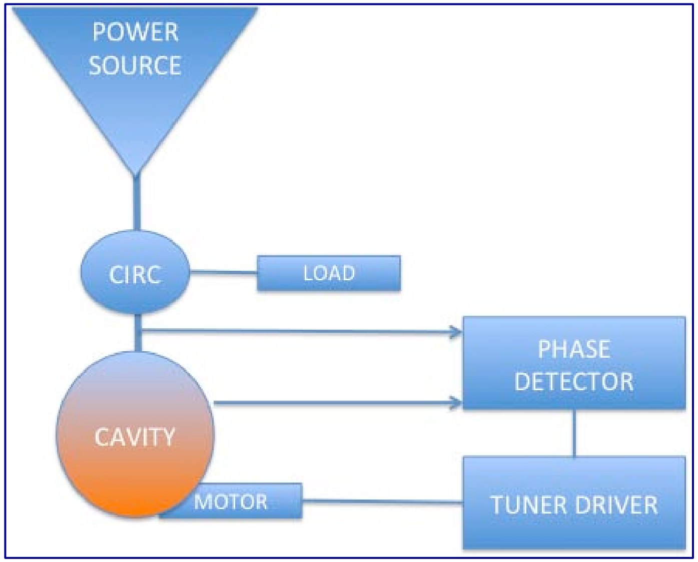
- ✓ The scope is to compensate for different effects, such as:
  - ✓ Ripple on high voltage supplies
  - ✓ Non linearities
  - ✓ Beam loading
  - ✓ Drifts
  - ✓ ………………
- ✓ The LLRF has also the task to control the tuning of the resonant cavity.
- ✓ In addition it can perform diagnostic and monitoring tasks.

- ✓ A typical LLRF system is composed of a number of integrated loops that accomplished the required tasks.
- ✓ In the last decades technology adopted has shifted from analogue electronics to digital LLRF system based on FPGA.

TASKS

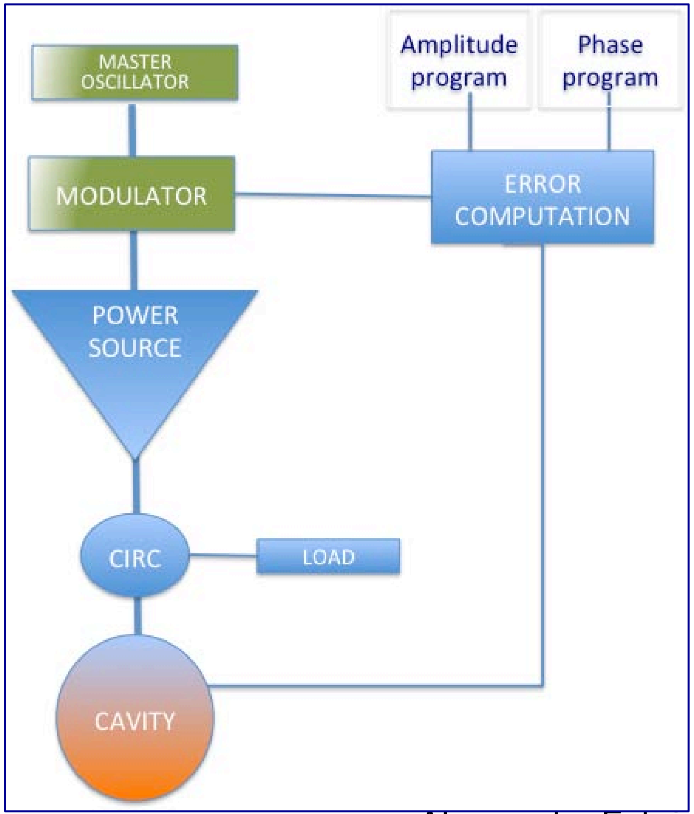
TUNING LOOP

- ✓ Keeps the cavity tuned compensated for cavity thermal drifts and beam loading.
- ✓ Phase comparison of signals from the cavity and at the cavity input
- ✓ Error signal drives the tuner



AMPLITUDE/PHASE LOOP

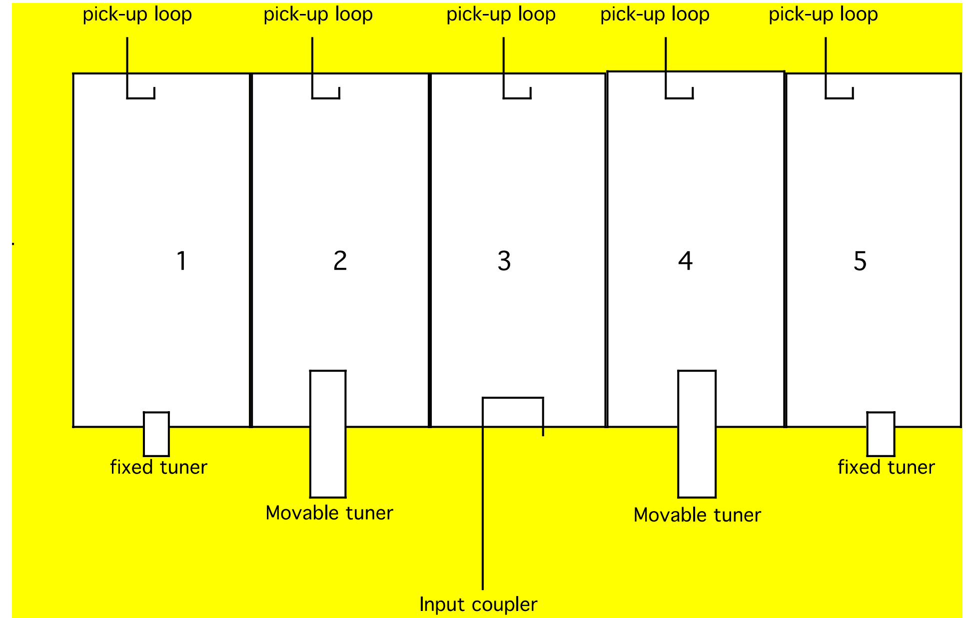
- ✓ Automatic control of amplitude and phase of the RF fields
- ✓ Beam loading compensation in storage rings
- ✓ Beam energy stabilization (linacs)
- ✓ Bunch timing stabilization (storage rings and linacs)
- ✓ Compares RF cavity sample with the set level.
- ✓ Error signals used to modulate the driving signal to power source



TASKS

AMPLITUDE BALANCE LOOP

- ✓ To avoid an excessive unbalance of the voltage between the cells in multicell cavities.
- ✓ *Ex. Applied to PETRA cavities:*
  - ✓ Amplitude ratio detector compares voltage in cells 2 and 4.
  - ✓ Errors signals drives the tuners differentially to balance the cells voltage



OTHERS

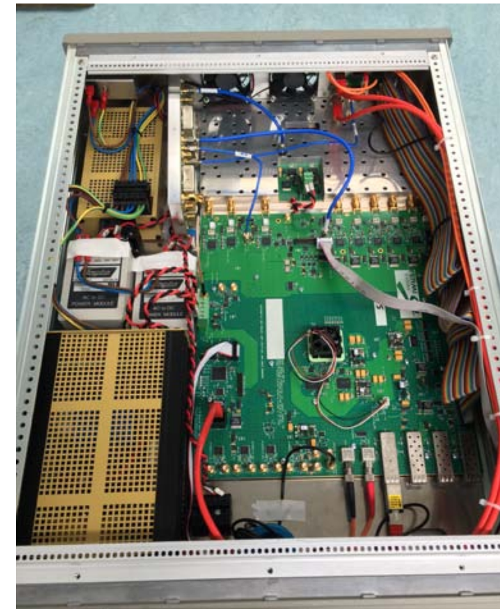
- ✓ Suppression of instabilities due to the interaction with the cavity accelerating mode in storage rings
  - ✓ combination of feedback loops (beam phase loop, direct RF feedback loop, ...) and/or beam feed-forward compensations.
- ✓ Tracking of the revolution frequency, RF phase jump and related controls at crossing of the transition energy (RF gymnastic).
- ✓ Controls of transient effects in pulsed regime or related to gaps in the filling
- ✓ Compensation of cable length variation due to drifts.

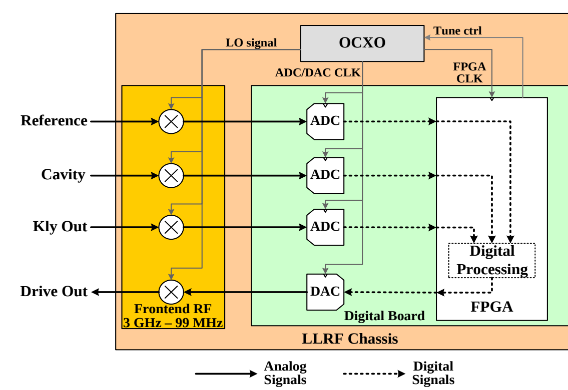
TECHNOLOGY

- ✓ Originally fully analog electronic systems
- ✓ Nowadays digital systems are generally adopted taking advantages of the huge potentiality of modern FPGAs (field programmable gate array),
- ✓ Advanced RF/analog technology is still essential for the success of a digital LLRF (front ends, signal conditioning, clock, etc).
- ✓ Therefore a digital LLRF is actually a mixed-signal system. Competence in both digital and RF/analog electronics are required to develop a LLRF system.
- ✓ Some features that can be reached with a digital system:
  - ✓ Higher precision
  - ✓ Lower noise
  - ✓ Flexibility (FPGA can be reprogrammed without the need of hardware changes)
  - ✓ Possibility of better diagnostics.

EXAMPLE FERMI LLRF

- ✓ Specification on amplitude and phase stability: 0.1% and 0.1° at 3 GHz.
- ✓ All-digital system, specifically developed for FERMI.
- ✓ System developed in the frame of a collaboration agreement between Elettra - Sincrotrone Trieste and Lawrence Berkeley National Lab.
  - ✓ Loops: amplitude, phase, cable calibration local oscillator phase drift and phase reference loop.
  - ✓ SLED: phase reversal and phase modulation.
- ✓ Final processing board, specifically designed for FERMI, will allow further firmware developments (for example intra-pulse feedback, real time communications between LLRF units, etc.). Installation is now completed for the main controllers





Amplitude stability with FERMI LLRF (0.030%)

Amplitude stability with FERMI LLRF (0.030%)

Phase stability with FERMI LLRF (0.046 deg@3GHz)

Phase stability with FERMI LLRF (0.046 deg@3GHz)

SUMMARY

- ✓ Radio Frequency Systems represent one of the major parts of any accelerator and a critical aspects to achieve the desired performance.
- ✓ Many technologies are involved.
- ✓ A good knowledge of beam physics is also involved.
- ✓ This lecture is just to give a taste of the many interesting aspects involved.
- ✓ Topics not covered include:
  - ✓ Derivation of cavity modes form Maxwell Equations
  - ✓ Computer simulation codes
  - ✓ Interaction with the beam
    - ✓ *Robinson instabilities*
    - ✓ *Longitudinal dynamics,*
    - ✓ *Coupled bunch instabilities*
  - ✓ ……………………………….

Thank you!

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